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OILSEED RADISH AGRO-POTENTIAL IN THE SYSTEM OF GREEN MANURE, BIOFUMIGATION, PHYTOREMEDIAL AND BIOENERGY USE

Scientific monograph

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The monograph explores the role and significance of oil radish among other cruciferous crops in fodder production, agriculture, and related sectors. It highlights its nutritional value, domestication, distribution, and current status.

The botanical, biological, and morphological characteristics of oil radish are detailed, along with descriptions of regionally adapted varieties and step-by-step cultivation technologies for both fodder and seed production

Particular attention is given to the effectiveness of oil radish in green manure systems, phytoremediation, and soil rehabilitation technologies. Its role in restoring degraded soils, stabilizing the agroecological condition of soil cover amid climate change, adapting fertilization strategies, and contributing to climate neutrality is emphasized.

The authors aim to showcase the value and versatility of oil radish as a key productive element in Ukraine's modern agricultural landscapes. Their analysis is grounded in long-term studies conducted by research institutions worldwide and is closely integrated with their own ongoing research within the framework of the state project «Development of environmentally friendly technologies for growing bioenergy crops to ensure energy independence and soil conservation for achieving climate neutrality» (State Registration No. 0124U000483).

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INTRODUCTION

For a long time, oil radish (*Raphanus sativus* L. var. *oleiformis* Pers.) was considered to be a rare plant. However, since the mid-1970s, it has been used in spring post-mowing and post-harvest crops in the system of conveyor production of green fodder. Very quickly, this crop conquered new areas for various purposes not only in the former Soviet Union, but also in Poland, Germany, the Netherlands, and Finland. The crop was firmly established as an extremely plastic and high-yielding species capable of growing from early spring to late autumn both in monoculture and in grass mixtures of various compositions, forming 30 to 70 t ha-1 of leaf mass balanced in terms of digestible protein content and valuable in terms of biochemical composition in terms of fiber structure, macro and microelements, and glucosinolates in 40–50 days of vegetation.

The multi-purpose study of this crop in different soil and climatic zones made it possible to formulate the main positive features that the crop potentially possesses: unpretentiousness to growing conditions and predecessor in crop rotation, high productivity and nutritional value, productive post-harvest and post-harvest use, high intensity of the root system functioning, relative tolerance to changes in sowing dates, fast growth rates, high positive response to mineral fertilization, high competitiveness to segetal vegetation, and possible

Despite a certain amount of research on the crop, its biological, physiological and technological aspects have a lot of contradictory data and generalizations. Like other agricultural crops, oil radish is unique and inimitable and in many respects requires rethinking of methodological approaches and assessments, reformatting of its cultivation technologies in view of the current level of technical equipment and purposes of use. This monograph will greatly contribute to this.

The authors of the monograph aimed to reveal the value and multifaceted nature of oil radish as an important productive element of modern agricultural landscapes of Ukraine based on the analysis of data from long-term studies of various research institutions around the world. The presented data of this generalization are closely intertwined with the authors' own research, which is still ongoing within the framework of the state theme "Development of environmentally friendly technologies for growing bioenergy crops to ensure energy independence and soil conservation for the formation of climate neutrality" (state registration number 0124U000483).

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CHAPTER 1. AGROBIOLOGICAL POTENTIAL OF OILSEED RADISH

1.1. Origin, range and introduction of oilseed radish

Oil radish is an older crop than sowing radish. It was introduced into culture primarily as an oilseed plant. That is why the first stages of its study were aimed at assessing its manufacturability as a source of valuable oil, which is not inferior to mustard oil and is easily hydrogenated. The cake obtained in the process of seed processing was an effective component in cattle feeding.

Oil radish, as well as winter rape and rape, is considered one of the oldest species on earth. However, its widespread introduction into culture continues to this day. The reasons for its limited distribution are insufficient awareness of cultivation technology and the lack of industrial seed processing. Under the planned system of management, this crop was not included in state plans, administrative institutions were not interested in it, and farmers did not report on the condition of their crops. At the same time, the area under this crop grew year after year abroad. The growth of this crop in the period 2005-2024 is due not only to its fodder value, but also to the possibility of using the oil obtained from its processing for the production of alternative biofuels (Tsytsiura, 2011).

The genus Raphanus L. (radish) is small in number of species. According to Ilyinska (2008), there are 1–2 or 8–10 species, including both wild and introduced plants that are widely used as vegetables. All presented forms are diploid, except for artificially produced tetraploid forms. The primary area of the genus is attributed to the Ancient Mediterranean (Mediterranean center of origin of cultivated plants) with traces of origin from the West Asian center, and over the period of several centuries the genus has spread significantly across different continents of the world (Figs. 1–2). The systematics of the species is still controversial and ambiguous. It is complicated by the ability to cross-pollinate between different branches of taxa with the formation of short-lived intermediate forms.

In the flora of Ukraine, the genus Raphanus is represented by several species, including the wild R. odessanus (Andr.) Sprengl., *R. raphanistrum* L., and *R. candidus* Worosch. And cultivated R. sativus. The origin and scope of phylogeny of these species is also a controversial issue, given the possible intraspecific hybridization of oil and seed radish (Ovcharenko, 2006) and other genetic recombinations (Pistrick, 1987).

More recently, R. acanthiformis J. M. Morel ex L. Sisley (Japanese radish – daikon) and R. chinensis Miller (Chinese radish) have been cultivated in Ukraine. Today, oil radish (*Raphanus sativus* L. var. *oleiformis* Pers.) is defined as a variety of sowing radish (*Raphanus sativus* L.), genus Raphanus L, under the division II of Raphanusae DC., division 5 of Brassiceae Hayek and belongs to the family Brassicaceae, order Capparidales, class Dicjtyledaneae. In recent publications, it is included in the group of varieties Convar. oleiferus L. – a group of varieties of oil radish with the following characteristics: annual plants, do not form a root crop, are grown for oil production from seeds and for fodder, vegetative and generative organs are similar to root forms.

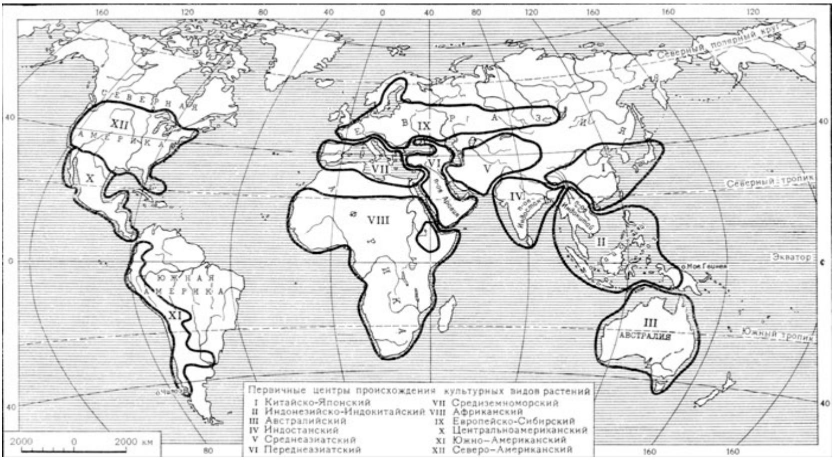


Figure 1.1 – Primary centers of origin of cultivated plants (current view) 1. Sino-Japanese; II Indonesian-Indochinese; III Australian; IV Hindustan; V Central Asian; VI West Asian; VII Mediterranean; VIII African; IX European-Siberian; X Central American; XI South American; XII North American (Centers of Origin of Cultivated Plants, 2024)

Detailed description of the Raphanus tribes (given in the original interpretation of the description by Swaamy, 2023):

– *R. sativus* (cultivated radish)

– *R. raphanistrum* (Wild Radish, or Jointed podded Charlock), a weed among barley, in Sweden. It is bristly, and has rather large, straw- coloured flowers.

– *R. sibiricus*, or Siberian Radish, has cylindrical pods.

– *R. caudatus*, the Java, or Rat's Tail Radish, a native of China, furnishes long, edible pods, purple or violet in colour. Type: Annual. They should be used half-grown. The root of this species is not used.

– *R. maritimus* (Maritime wild radish) an indigenous, seaside variety. A large, straggling plant, often more than 1m in height, covered in a cloud of pale yellow flowers in May and June. hard pod with a beaded appearance due to constrictions between each seed. Leaves are toothed and pinnate, and covered in coarse bristles

– *R. erucoides*, of Italy, has pods with a beak of their own length, and a simple, biennial root, scarcely thicker than the stem.

– *R. tenellus*, another native of Siberia, flowers in Britain in June and July, having awl-shaped, jointed, two-celled, smooth pods. The leaves are oblanceolate to elliptic-oblong, with sinuous or coarsely-toothed leaf edges.

According to Swaamy (2023) the cultivated radishes have several wild relatives such as *R. raphanistrum* and its supbspecies viz, *R. raphanistrum* subsp. Landra (Moretti ex DC.) Bonnier & Layens, *R. raphanistrum* subsp *maritimus* (Sm.) Thell., *R. raphanistrum* subsp *microcarpus* (Lange) Thell., *R. raphanistrum* subsp *raphanistrum*, *R. raphanistrum* subsp *rostratus* (DC.) Thell., and *R. confusus* (Greuter & Burdet) Al-Shehbaz & Warwick. Sometimes these related species are considered as one species complex named R. raphanistrum, with the different taxa classified as subspecies. *R. sativus* crosses freely with the related wild species. *R. sativus* is also closely related to several Brassica species and to Sinapisarvensis (charlock), with which it has also been successfully crossed (CABI, 2019; CABI, 2022; NPT. 2022).

Botanical Varieties of Radish (WIKI, 2022):

– *Raphanus acanthiformis* M. Morel ex Sisley (Mansf) -> *Raphanus sativus* L. (Longipinnatus Group)

– *Raphanus caudatus* L. (GRIN) (NOPD) -> Raphanus sativus L. (Caudatus Group)

– *Raphanus caudatus* L. f. (Mansf) -> Raphanus sativus L. (Caudatus Group)

– *Raphanus chinensis* Mill. (Mansf) (NOPD) -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD)

– *Raphanus indicus* Sinskaya -> Raphanus sativus L. (Caudatus Group)

– *Raphanus macropodus* H.Lév. (NOPD)

– *Raphanus monnetii* H.Lév. (NOPD)

– *Raphanus niger* Mill. (NOPD) -> *Raphanus sativus* L. var. niger J. Kern. (Mansf) (GRIN)

– *Raphanus oleifer* hort. ex Steud. (NOPD) -> Raphanus sativus L. var. oleiformis Pers. (GRIN) (NOPD)

– *Raphanus officinalis* Crantz (NOPD)

– *Raphanus orbicularis* Mill. (NOPD)

– *Raphanus radicula* Pers. (NOPD) -> *Raphanus sativus* L. (Radicula Group)

– *Raphanus radicula* (Pers.) Alef. (Mansf) -> Raphanus sativus L. (Radicula Group)

– *Raphanus raphanistroides* (Makino) Nakai (NOPD) (Mansf)

– *Raphanus raphanistrum* L. (GRIN)

– *Raphanus raphanistrum* L. subsp. caudatus (L.) Thell. (NOPD) -> *Raphanus sativus* L. (Caudatus Group)

– *Raphanus raphanistrum* L. subsp. caudatus (L. f.) Thell. (Mansf) -> *Raphanus sativus* L. (Caudatus Group)

– *Raphanus raphanistrum* L. subsp. sativus (L.) Domin (NOPD) -> *Raphanus sativus* L. subsp. sativus

– *Raphanus raphanistrum* L. subsp. sativus (L.) Schmalh. -> *Raphanus sativus* L. subsp. sativus

– *Raphanus raphanistrum* L. var. niger (Mill.) P. Fourn. (NOPD) -> *Raphanus sativus* L. var. niger J. Kern. (Mansf) (GRIN)

– *Raphanus raphanistrum* L. var. radicula (Pers.) P. Fourn. (NOPD) -> Raphanus sativus L. (Radicula Group)

– *Raphanus raphanistrum* L. var. sativus (L.) Beck (NOPD)

– *Raphanus rotundus* Mill. (NOPD) -> *Raphanus sativus* L. (Radicula Group)

– *Raphanus sativus* L. (GRIN)

– *Raphanus sativus* L. (Caudatus Group) (MMPND)

– *Raphanus sativus* L. (Chinensis Group) (MMPND)

– *Raphanus sativus* L. (Fodder Radish Group) -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD) *A*

– *Raphanus sativus* L. (Hortensis Group) -> *Raphanus sativus* L. (Radicula Group) (MMPND)

– *Raphanus sativus* L. (Japonicus Group) -> *Raphanus sativus* L. (Longipinnatus Group) (MMPND)

– *Raphanus sativus* L. (Longipinnatus Group) (MMPND)

– *Raphanus sativus* L. (Mougri Group) -> *Raphanus sativus* L. (Caudatus Group) (MMPND)

– *Raphanus sativus* L. (Oleiformis Group)

– *Raphanus sativus* L. (Radicula Group) (MMPND)

– *Raphanus sativus* L. subsp. *acanthiformis* (Blanch.) A. K. Stankevich -> *Raphanus sativus* L. (Longipinnatus Group) (MMPND)

– *Raphanus sativus* L. subsp. *acanthiformis* (Morel) A. K. Stankevich -> *Raphanus sativus* L. (Longipinnatus Group) (MMPND)

– *Raphanus sativus* L. subsp. *acanthiformis* (M. Morel ex Sisley) Stankev. (Mansf) -> *Raphanus sativus* L. (Longipinnatus Group)

– *Raphanus sativus* L. subsp. *esculentus* (Metzg.) Alef. -> *Raphanus sativus* L. (Radicula Group)

– *Raphanus sativus* L. subsp. *oleiferus* (Stokes) Metzg. (Mansf) (NOPD) -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD) *A*

– *Raphanus sativus* L. subsp. *raphanistroides* (Makino) Sazon. (Mansf) -> *Raphanus raphanistroides* (Makino) Nakai (NOPD) (Mansf)

– *Raphanus sativus* L. subsp. *sativus*

– *Raphanus sativus* L. subsp. *sativus* convar. *radicula* (Pers.) Sazon. (Mansf) -> *Raphanus sativus* L. (Radicula Group)

– *Raphanus sativus* L. subsp. *sativus* convar. *sativus* (Alef.) Sazon. (Mansf) -> *Raphanus sativus* L. subsp. sativus

– *Raphanus sativus* L. subsp. *sinensis* L.V. Sazonova & A. K. Stankevich -> *Raphanus sativus* L. (Chinensis Group)

– *Raphanus sativus* L. subsp. *sinensis* Sazon. & Stankev. (NOPD) -> *Raphanus sativus* L. (Chinensis Group)

– *Raphanus sativus* L. subsp. *sinensis* Sazon. & Stankev. convar. lobo Sazon. (Mansf) -> *Raphanus sativus* L. (Chinensis Group)

– *Raphanus sativus* L. subsp. *sinensis* Sazon. & Stankev. convar. oleiferus (Stokes) Sazon. & Stankev. -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD) *A*

– *Raphanus sativus* L. subsp. *sinensis* Sazon. & Stankev. convar. sinensis Sazon. (Mansf) -> *Raphanus sativus* L. (Chinensis Group)

– *Raphanus sativus* L. var. *acanthiformis* Makino -> *Raphanus sativus* L. (Longipinnatus Group)

– *Raphanus sativus* L. var. *acanthiformis* Makino fo. raphanistroides Makino -> *Raphanus raphanistroides* (Makino) Nakai (NOPD) (Mansf)

– *Raphanus sativus* L. var. *campestris* hort.

– *Raphanus sativus* L. var. *caudatus* Alef. -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD) *A*

– *Raphanus sativus* L. var. *caudatus* (L.) L.H. Bailey (NOPD) (GRIN) *A* -> *Raphanus sativus* L. (Caudatus Group)

– *Raphanus sativus* L. var. *caudatus* (L.) Vilmorin -> *Raphanus sativus* L. (Caudatus Group) ?

– *Raphanus sativus* L. var. *caudatus* (L. f.) Vilmorin (Mansf) -> *Raphanus sativus* L. (Caudatus Group) ?

– *Raphanus sativus* L. var. *chinensis* Gall. -> *Raphanus sativus* L. (Chinensis Group)

– *Raphanus sativus* L. var. *chinensis* (Mill.) Alef. (NOPD) -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD) *A*

– *Raphanus sativus* L. var. *hortensis* Baker -> *Raphanus sativus* L. subsp. sativus

– *Raphanus sativus* L. var. *hortensis* Baker f. *acanthiformis* Makino -> *Raphanus sativus* L. (Longipinnatus Group)

– *Raphanus sativus* L. var. *hortensis* Baker f. raphanistroides Makino -> *Raphanus raphanistroides* (Makino) Nakai (NOPD) (Mansf)

– *Raphanus sativus* L. var. *longipinnatus* L.H. Bailey (GRIN) (NOPD) -> *Raphanus sativus* L. (Longipinnatus Group)

– *Raphanus sativus* L. var. *minor* J. Kern. (Mansf) (NOPD)

– *Raphanus sativus* L. var. *mougri* Helm. (NOPD) (Mansf) -> *Raphanus sativus* L. (Caudatus Group) ?

– *Raphanus sativus* L. var. *niger* (Miller) Pers. -> *Raphanus sativus* L. var. niger J. Kern. *A*

– *Raphanus sativus* L. var. *niger* (Miller) S. Kerner -> *Raphanus sativus* L. var. *niger* J. Kern. *A*

– *Raphanus sativus* L. var. *niger* (Mill.) J. Kern. (NOPD) -> *Raphanus sativus* L. var. niger J. Kern. (Mansf) (GRIN)

– *Raphanus sativus* L. var. *niger* J. Kern. (Mansf) (GRIN)

– *Raphanus sativus* L. var. *oblongus* DC. (NOPD)

– *Raphanus sativus* L. var. *oleiferus* Stokes (GRIN) (NOPD) -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD)

– *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD) *A*

– *Raphanus sativus* L. var. *radicula* Pers. (Mansf) (NOPD) -> *Raphanus sativus* L. (Radicula Group)

– *Raphanus sativus* L. var. *raphanistroides* (Makino) Makino (NOPD) -> *Raphanus raphanistroides* (Makino) Nakai (NOPD) (Mansf)

– *Raphanus sativus* L. var. *rotundus* (Mill.) DC. (NOPD) -> *Raphanus sativus* L. (Radicula Group)

– *Raphanus sativus* L. var. *sylvestris* Koch (NOPD) -> *Raphanus raphanistrum* L.

– *Raphanus sativus* L. var. *sativus* (GRIN) -> *Raphanus sativus* L. subsp. *sativus*

– *Raphanus sativus* L. convar. *caudatus* (L. f.) Pistrick (Mansf) -> *Raphanus sativus* L. (Caudatus Group) ?

– *Raphanus sativus* L. convar. *oleifer* (Stokes) Alef. (Mansf) -> *Raphanus sativus* L. var. *oleiformis* Pers. (GRIN) (NOPD)

– *Raphanus sativus* L. f. *raphanistroides* Makino (NOPD) -> *Raphanus raphanistroides* (Makino) Nakai (NOPD) (Mansf)

– *Raphanus sinensis* Sinskaya (Mansf) -> *Raphanus sativus* L. (Chinensis Group)

– *Raphanus sylvestris* Lam. -> *Raphanus raphanistrum* L.

The origin of the oil radish – *Raphanus sativus* L. var. *oleiformis* Pers. is also currently controversial. The description of the general genetic structure of the cruciferous family was carried out by Sinska (Filatenko et al., 2003). Her works (Synska, 1926, 1928, 1931, 1948, 1963, 1969) emphasize its origin in East Asia. There are hypotheses that oil radish was cultivated in prehistoric times in the Middle East, and in particular in Egypt, as an oil plant.

The research of Bloimer (1901) points to the origin of oil radish from the common wild radish. However, it is noted that it may be an older form than the wild radish. The same opinion was shared by other researchers on this issue (Gereau, 1923). It is reported that the systematics of cruciferous plants, in particular the genus Raphanus, is one of the most complex and there is still no final opinion on its hierarchy. There are a number of different approaches to the genetic interpretation of the relationships of the genus Raphanus. One of the most thorough is the variant presented in the works of Synska, however, another monograph on the genus Raphanus by Zhukovsky (1971) did not share her views on the species differentiation of Brassica. In his studies, it was repeatedly emphasized that the main thing is to understand the species as a three-dimensional taxon. Among cultivated Brassica there are many cultivars that do not have botanical and genetic rights to the rank of species. The cytogenetics of Brassica is still poorly developed. We have some idea of the very complex evolution of Brassica, but under these conditions we should proceed from the understanding of the species as a large taxon with intraspecific complex differentiation. According to Zhukovsky (1971), approaches to this problem based only on the morphological clade of the species are wrong.

These features are noted in the studies of Synska's predecessors, who unilaterally considered the issue of the genetic origin of oil radish in view of its morphogenetic structure. Thus, Batalin (1879) and Fedorov (1912) attributed this plant to the wild ancestors of cultivated radish varieties. Kalinovsky (1980, 1982) believed that oil radish originated from China and Japan as a form of garden radish.

Blomeyer (1901) refers to it as a type of garden radish with the primary center of origin in western Asia, between Palestine and the Caucasus from the field radish (rape, swarup) *Raphanus raphanistrum* L.

The same conclusions were made by D. N. Pryanishnikov (Werner, 1985), ignoring the different color of the petals. He explained this discrepancy by the fact that *Raphanus raphanistrum* L. has purple streaks in yellow petals on some soils.

On the other hand, Komarov (1938) and Decandol (1985) denied the origin of oil radish from field radish. In support of this, they pointed out that ancient peoples could not pay attention to the field weed and improve it to obtain edible roots, but they did not deny the European origin of the genus Raphanus, despite the fact that the inhabitants of India, China, and Japan have been growing radish since ancient times.

In contrast to these claims, Komarova (1938) points to the East Asian origin of the oil radish: in the course of economic relations between the peoples of China and Central Asia, it spread to Asia. This fact has been confirmed by archaeological research.

Figure 1.2 – Oilseed radish in crops on the experimental field of Vinnytsia National Agrarian University (in different years of the period 2013–2024)

Shlapunov (1982) considers *Raphanus maritimus* Sm. to be the most likely ancestor of the radish, which grows off the coasts of northern Spain, Ireland, Scotland and Britain. It is a biennial plant with yellow flowers and the same spongy fruits as the cultivated radish. Komarov (1938) and Mikhailova (1975) in their dissertations, based on scientifically based results, also argue that Raphanus raphanistrum L. does not correspond to the flora of Asia.

Karpechenko (1968, 1974) genetically approximates wild radish with the seed radish on the basis of the same number of chromosomes – 18. However, he notes that this fact is evidence of a common ancestor of the genus Raphanus.

Synska in her early works (1926, 1928, 1931) believed that the homeland of radish crops was China and suggested that a wild weed form, the ancestor of radish, would be found in eastern China or another area. She emphasized the fact that many Chinese and Japanese forms of root radishes did not produce thickened roots under the conditions of a longer northern day, bloomed quickly, and were morphologically similar to oil radish.

Based on the results of her experiments on hybridization of oil radish with radish, seed radish and wild radish, Sinnaya (1926) concluded that the roots of wild radish and oil radish are of genetically different nature, that oil radish is heterozygous in terms of root traits and that by selection it is possible to obtain a genus with thick, hard roots, i.e., similar in appearance to wild forms of the root crop. In her later works, Sinnia (1963, 1969) suggested its more likely origin from ancient Egypt. She also pointed to the insufficient study of the variability of its morphotypes. Some of its forms have the same fruit structure as the Chinese radish. She admits the possibility that oil radish is a fine-rooted form of radish: in China, of Chinese origin, and in Europe, of European origin. Some foreign authors Kovarskaya, Lysakova, Geishin and Rosenthal (Sinskaya, 1969) believe that oil radish originates from the common sowing radish, since under the influence of temperature and day length, the root form can produce plants without roots, but with the formation of a flower stem and seeds.

Thus, according to Radchuk and Blum (2005), the question of the genetic and geographical origin of oil radish remains open. Recent studies on the origin of oil radish have been translated into the perspective of species genetic analysis and genetic phylogeny and have been concentrated mainly in foreign research institutions (Pistrick, 1987; Ohnishi, 1999; Huh and Ohnishi, 2002; Warwick and Sauder, 2005; Yamane and Ohnishi, 2005; Huh and Choi, 2006).

Systematized data on the taxonomy and origin of oil radish are presented in the form of a grouped data set below.

Raphanus sativus* var. *oleiformis

Vernacular names:

- English: fodder radish, oil radish, oilseed radish
- Deutsch: Ölrettich
- Español: rábano oleaginoso
- Français: radis fourrager, radis oléifère
- Hornjoserbsce: Wolijowa rjetkej
- Magyar: olajretek
- Italiano: rafano da foraggio
- Nederlands: Bladrammenas
- Português: rábano-de-azeite, nabo-forrageiro
- Türkçe: kestane turbu
- Portuguese: rabão-de-azeite
- Spanish: rabano oleaginoso
- Swedish: oljerättika

Taxonomy ID: 463157 (for references in articles please use NCBI:txid463157) current name

Raphanus sativus* var. *oleiformis Pers. (Persoon), 1806

- [or *R. sativus* Leaf Radish Group]
- Persoon, in indicating 'chinensis oleiformis' and citing 'Willd. Sp. III. p. 560' under this species, provided an indirect reference to the diagnosis 'R. chinensis annuus oleiferus' of the unnamed variety of Willdenow and Linnaeus (Sp. pl. ed. 2, 2:935. 1763) (Shenzhen ICN 38.14)

NCBI BLAST name: **eudicots**

Rank: **varietas**

Genetic code:

```
  AAs  = FFLLSSSSYY**CC*WLLLLPPPPHHQQRRRRIIIMTTTTNNKKSSRRVVVVAAAADDEEGGGG
Starts = ---M------**--*----M---------------M----------------------------
Base1  = TTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCAAAAAAAAAAAAAAAAGGGGGGGGGGGGGGGG
Base2  = TTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGG
Base3  = TCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAG
```

Mitochondrial genetic code:

```
  AAs  = FFLLSSSSYY**CCWWTTTTPPPPHHQQRRRRIIMMTTTTNNKKSSRRVVVVAAAADDEEGGGG
Starts = ----------**----------------------MM---------------M------------
Base1  = TTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCAAAAAAAAAAAAAAAAGGGGGGGGGGGGGGGG
Base2  = TTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGG
Base3  = TCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAG
```

Plastid genetic code:

```
  AAs  = FFLLSSSSYY**CC*WLLLLPPPPHHQQRRRRIIIMTTTTNNKKSSRRVVVVAAAADDEEGGGG
Starts = ---M------**--*----M---------------M----------------------------
Base1  = TTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCAAAAAAAAAAAAAAAAGGGGGGGGGGGGGGGG
Base2  = TTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGGTTTTCCCCAAAAGGGG
Base3  = TCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAG
```

Other names heterotypic synonym:

Raphanus chinensis Mill., Gard. Dict. ed. vol. 8, no. 5. 1768.

Raphanus sativus var. *oleiformis* Pers. Syn. vol. 2, 482. 1812.

Raphanus sativus var. *oleiferus* Stokes, Bot. Mat. Med. vol. 3, 482. 1812.

Raphanus sativus var. *chinensis* (Mill.) Alef., Landw. Fl., 258. 1866.

Raphanus sativus convar. *oleiferus* (Stokes) Sazon. & Stankev., Kult. Fl. SSSR vol. 18, 209, comb. superfl. 1985.

Raphanus raphanistrum f. chinensis (Mill.) Thell. in Hegi,, Ill. Fl. Mittel-Eur. vol. 4, 1, 280-281. 1918.

Raphanus sativus subsp. *oleiferus* (Stokes) Metzg. Landw. Pflanzenk. vol. 2, 1059. 1841.

Raphanus raphanistrum f. *longirostris* Thell. in Hegi, Ill. Fl. Mittel-Eur. vol. 4, 1, 280-281. 1918.

Raphanus sativus L., Sp. Pl. ed. vol. 2, 935, quoad γ. 1763.

Raphanus sativus var. *caudatus* Alef., Landw. Fl., 258. 1866., non , non var. caudatus Vilm. 1925 (non R. caudatus L.f. 1767).

Lineage *(full):* cellular organisms; Eukaryota; Viridiplantae; Streptophyta; Streptophytina; Embryophyta; Tracheophyta; Euphyllophyta; Spermatophyta; Magnoliopsida; Mesangiospermae; eudicotyledons; Gunneridae; Pentapetalae; rosids; malvids; Brassicales; Brassicaceae; Brassiceae; Raphanus; Raphanus sativus ***APG IV Classification***: Domain: Eukaryota • (unranked): Archaeplastida • Regnum: Plantae • Cladus: Angiosperms • Cladus: eudicots • Cladus: core eudicots • Cladus: superrosids • Cladus: rosids • Cladus: eurosids II • Ordo: Brassicales •

Familia: Brassicaceae • Tribus: Brassiceae • Genus: Raphanus • Species: Raphanus sativus Pers., 1806.

CollapseTaxonomy

Kingdom	Plantae
Subkingdom	Viridiplantae
Infrakingdom	Streptophyta
Superdivision	Embryophyta
Division	Tracheophyta
Subdivision	Spermatophytes
Order	Brassicales
Family	Brassicaceae
Tribe	Brassiceae
Genus	Raphanus
Species	Raphanus sativus
Variety	Raphanus sativus var. oleiformis

KingdomPlantae (1PLAK)
PhylumMagnoliophyta (1MAGP)
ClassAngiospermae (1ANGC)
CategoryMalvids (1MAVD)
OrderBrassicales (1CAPO)
FamilyBrassicaceae (1CRUF)
GenusRaphanus (1RAPG)
SpeciesRaphanus sativus subsp. oleiferus (RAPSO)

Associated Non-Taxonomic

brassica arable crops (3BRAC)

CollapseAuthority file

NCBI taxonomy ID: 463157
BioLib taxon ID: 132243
GBIF taxon ID: 4928064
Tropicos ID: 50156489
GRIN URL: https://npgsweb.ars-grin.gov/gringlobal/taxonomydetail.aspx?id=319666
PfaF ID: Raphanus sativus oleiformis
uBio ID: 5877259
Plants of the World Online ID: urn:lsid:ipni.org:names:2911259-4

EPPO Code: RAPSO

- ***Preferred name***: Raphanus sativus subsp. oleiformis
- ***Authority***: Persoon, Stokes, Metzger

1.2. Mophological portfolio of oilseed radish

Oilseed radish is characterized by a number of morphobiological features that qualitatively distinguish the crop from other cabbages.

Its root is taproot (Figure), thickened in diameter to 2–3 cm near the root collar. Thickening can reach even higher values of up to 4–6 cm and is determined by the sowing time and the area of plant nutrition (Tsytsiura and Tsytsiura, 2015, Figures 1.3–1.10). The depth of root penetration depends on the mechanical composition of the soil: on light soils it reaches values up to 60–80 cm, and on heavier soils – 50–60 cm. The bulk of the roots are located at a depth of 25–30 cm, which should be taken into account in the crop's agricultural technology.

The most intensive growth of the root system of oilseed radish is observed from the rosette phase to the budding phase. In the northern regions, the growth of the root system in the interphase period of germination – budding was 1.1 cm day^{-1}, budding – flowering – 0.6 cm day^{-1}, flowering – physiological maturity 0.3 cm day^{-1}. Moreover, in some studies it is noted that in the northern latitudes the growth of the root system is limited to the interval of 0.5–0.7 cm day^{-1} (Tsytsiura and Tsytsiura, 2015), and when oil radish moves south – 0.8–1.3 cm day^{-1} (Kengbaev, 1986).

The development of the root system of oil radish is determined by the natural and climatic zone of its cultivation and the timing of sowing. Thus, according to Kuznetsov (1976), the roots of oil radish under optimal growing conditions can penetrate the soil to a depth of 1 m. Pilyuk (1984) studied the depth of penetration of oil radish roots 30, 45 and 60 days after sowing (Table 1.1) in spring post-cutting and post-harvest crops. Her observations showed that on medium loamy sod-podzolic soils, 60 days after sowing, the root system of oil radish penetrates to a depth of 57.3 cm in spring, 70.1 cm in post-cutting and 57.8 cm in post-harvest crops. The most intensive average daily root growth occurs in radish during the budding-flowering period, i.e. 45–60 days after sowing in spring (1.5 cm) and (1.90 cm) in post-harvest crops.

Figure 1.3 – Roots of oil radish plants in the period of cotyledon leaves (electronic magnification 200x using a Sigeta Cam USB microscope hereafter)

Figure 1.4 – The area of the root collar of oil radish variety Raduga during the formation of true leaves (the characteristic anthocyanin color of the upper part of the root is noticeable)

Figure 1.5 – Root system of oilseed radish variety Zhuravka during budding with active formation of the suction zone (electronic magnification 200x)

Figure 1.6 – General view of oil radish (Vavilov and Balyshev, 1984): 1, 2 – plants in the phases of flowering – fruit formation and germination; 3 – upper part of the stem in the flowering phase; 4 – fruit; 5 – seeds (upper position – enlarged)

Figure 1.7 – The nature of the development of the root system of the variety 'Raduga' in the phase of the beginning of stemming on the example of 7 plants sequentially selected along the length of the row (seeding rate of 2.0 million units/ha of similar seeds on the background of $N_{60}P_{60}K_{60}$, 2011)

Figure 1.8 – Variation in the development of the root system of oilseed radish plants of 'Zhuravka' variety during the period of rosette formation

Figure 1.9 – Root diameter at the base of the root collar of oilseed radish variety 'Zhuravka' depending on the seeding rate (from left to right: 0.5 million, 1.0 million, 1.5 million, 2.0 million, 3 million germinating seeds per hectare)

Figure 1.10a – Cross-section of root thickening of oilseed radish at different magnifications

Table 1.1

Growth and average daily growth of the root system of oil radish, cm (cm day^{-1}) Pyluk (1984)

Sowing option	30 days after sowing		45 days after sowing		60 days after sowing	
Spring sowing	19.6	0.65	34.7	1.01	57.3	1.51
Post-cutting	22.5	0.75	41.7	1.28	70.1	1.90
Post-harvest	27.3	0.91	44.6	1.15	57.8	0.88

In the post-harvest crops for all years of research, more intensive development of the root system was noted 30–45 days after sowing, which reached 1.15 cm per day. In the future, the intensity of growth of oil radish roots in post-harvest crops decreases the most intensive growth of the root system of oil radish in the first 30 days after sowing is observed in post-harvest crops and averages 0.91 cm per day. In 45–60 days after sowing, more active root growth of this crop was observed in post-harvest crops (1.28 and 1.90 cm per day). In general, oil radish is characterized by a fairly intensively developed root system, capable of penetrating under favorable conditions during 60 days of vegetation to a depth of 65–75 cm. At the same time, the nature of root distribution depends on the soil and climatic zone of crop cultivation. For example, in the northern regions of the Eurasian continent, the root system of oil radish is concentrated in the 0-25 cm horizon (up to 70–75% of roots), and the soil layer of 20-70 cm accounts for 12–25% of roots (Figure 1.11–1.14 (a–d).

In central areas with sufficient moisture, the ratio in the distribution of the root system shifts to deeper horizons. Thus, the soil layer of 0–25 cm already accounts for 45–65% of the roots, and deeper horizons account for up to 25–35%.

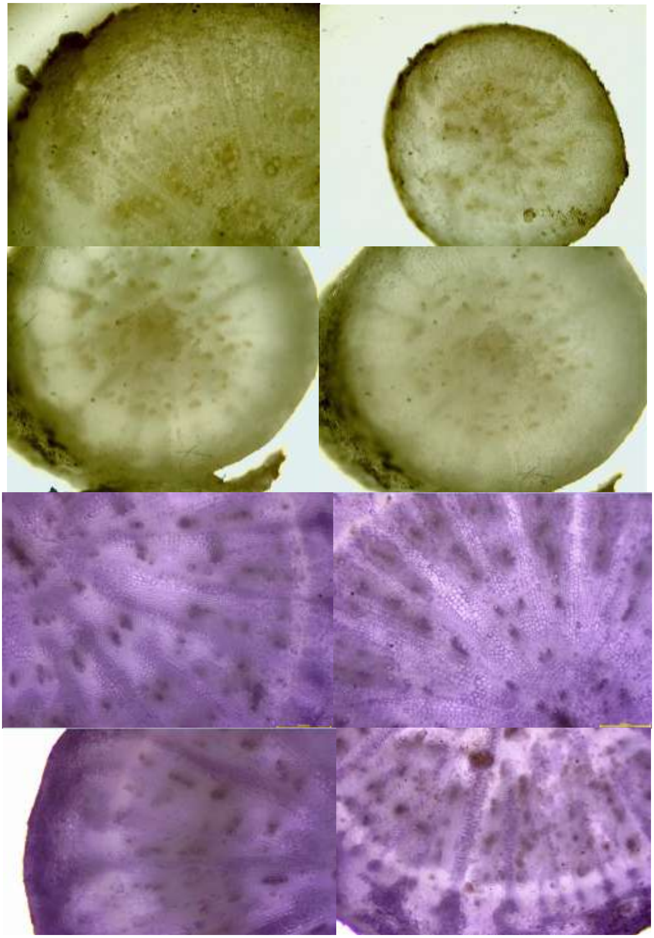


Figure 1.10b – Cross-section of root thickening of oilseed radish at different magnifications

It should be noted that in arid zones and areas of the Far North of the Eurasian continent, the productivity of the root system of oil radish is 4.50–5.70, which positively distinguishes it among a number of traditional agricultural crops.

Figure 1.11 – Longitudinal section of oilseed radish root thickening in the suction zone

Figure 1.12– Root system of oilseed radish 'Zhuravka' variety during the fruiting period

Figure 1.13 – Variation series of root thickening development of oil radish plants of 'Zhuravka' variety depending on the seeding rate (from left to right 3, 2, 1.5, 0.5 million germinating seeds/ha), 2012

Figure 1.14 – Nature of root system development in plants selected from an area of 0.25 m² for 'Raduga' variety at a sowing rate of 1.5 million seeds/ha of similar seeds with $N_{60}P_{60}K_{60}$, 2012

Figure 1.14a – Root systems of oilseed radish at the seedling stage (BBCH 6–8) and rosette stage (BBCH 12–16)

Figure 1.14b – Variants of morphometry of oilseed radish roots in the phenological phase of flowering (BBCH 58–64)

Figure 1.14c – Comparison of the morphometry of the root systems of oilseed radish and other typological representatives of cruciferous species

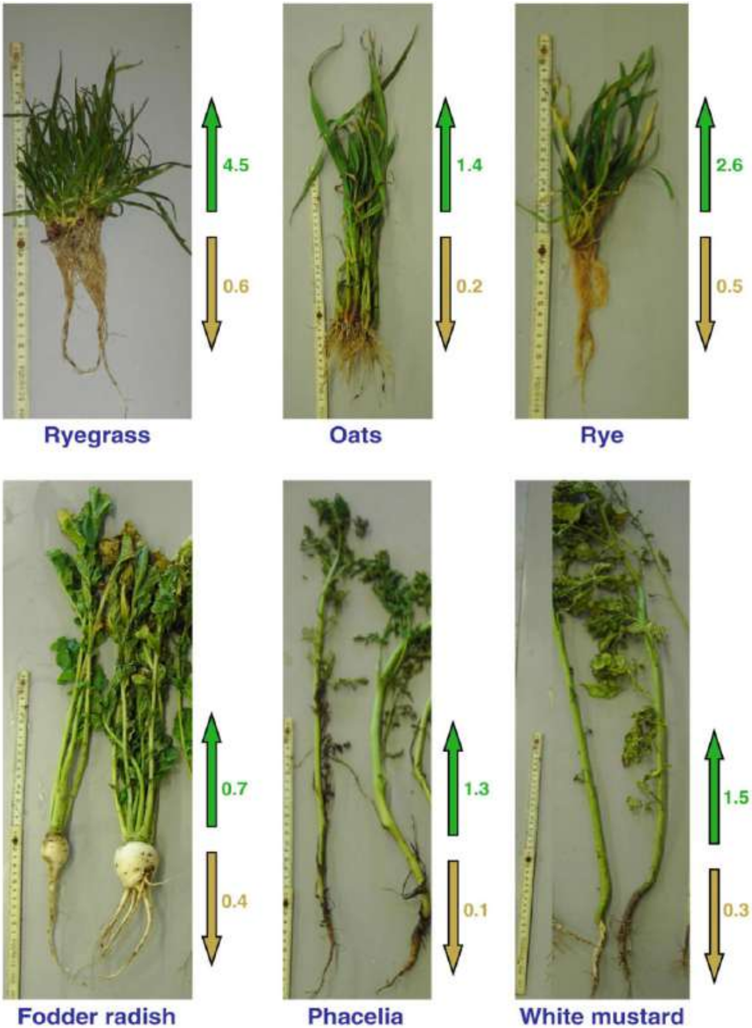


Figure 1.14d – Illustration of above-ground and below-ground biomass of 6 cover crops with indication of the allocation of biomass to roots (downward arrow) and shoots (upward arrow). Values are in tons (t) dry matter ha^{-1} (Baets et al., 2011)

The stem of oil radish is capable of branching (Figures 1.15–1.16), curved at the nodes in cross-section, 3–5 faceted, and has intense pubescence. The color of the plants of the crop is a varietal trait that varies from intense green to bluish-green. The color of plants in oil radish is an additional indicator of mineral nutrition (Zinchenko, 2005), a reaction to stress factors (Krivitsky et al., 1981), and a criterion of ripening (Shpaar, 1999). The vast majority of oil radish varieties of domestic selection have a light green color, and varieties of foreign selection have an intense green color (Batarchuk, 1990). The stem is hollow during flowering – full ripeness, but the nature of its fullness depends on the phenological phase of plant development, their water content during the growing season, temperature conditions during budding – flowering, and plant nutrition area (Figures 1.17–1.25).

Figure 1.15 – Formation of lateral shoots in the axils of the leaf blade petiole in oilseed radish (‘Raduga’ variety) (lateral shoots appear, as a rule, in the axils of 3–6 leaves)

Thus, during the period of stem formation (stemming phase), plants are characterized by a fully filled stem with juicy parenchyma. When the stem is cut during this phase, active sap flow is observed. The formation of heart-shaped parenchyma, which in oil radish has a bright white or cream color, begins from the stemming phase, so that at the budding stage, signs of its presence are visible on the cross-section of the stem in the naked eye in the young parts of the stem (Figures 1.16).

Figure 1.16 – Lateral shoots in the axils of the petiole of the leaf blade in oilseed radish 'Zhuravka' variety

Subsequently, in the course of plant maturation, qualitative transformations in the filling tissues of the stem cause maceration of the stem core and morphogenesis of the stem tissues of the hypodermal ring, accompanied by an increase in the proportion of mechanical tissues, an increase in the percentage of fiber in the leaf-stem mass and a decrease in its moisture content.

Figure 1.17 – The nature of pubescence of the stem of oilseed radish variety 'Raduga'

Figure 1.18 – Transverse section of an oil radish stem of 'Zhuravka' variety at the beginning of stemming (signs of the core are not clearly visible and not clearly expressed)

Figure 1.19 – Transverse section of an oil radish stem of the 'Raduga' variety at the beginning of stemming (the central core is not expressed, only formed)

Figure 1.20 – The formed core of the stem of oilseed radish variety 'Zhuravka' at the phenological phase of budding

Figure 1.21 – Filling parenchyma of the plant stem during the period of stemming – budding

Figure 1.22 – The beginning of maceration of the stem core during the flowering period of oilseed radish variety 'Zhuravka'

Figure 1.23 – Oilseed radish stem in cross-section in the flowering phase (upper position – peduncle zone, lower position – zone of the lower root part of the stem)

Figure 1.24 – Transverse section at the base of the stem of Zhuravka variety in the phase of green pod with pronounced maceration of its core (250x electronic magnification)

Figure 1.25a – Longitudinal section of the stem of Zhuravka variety (electronic magnification 200x)

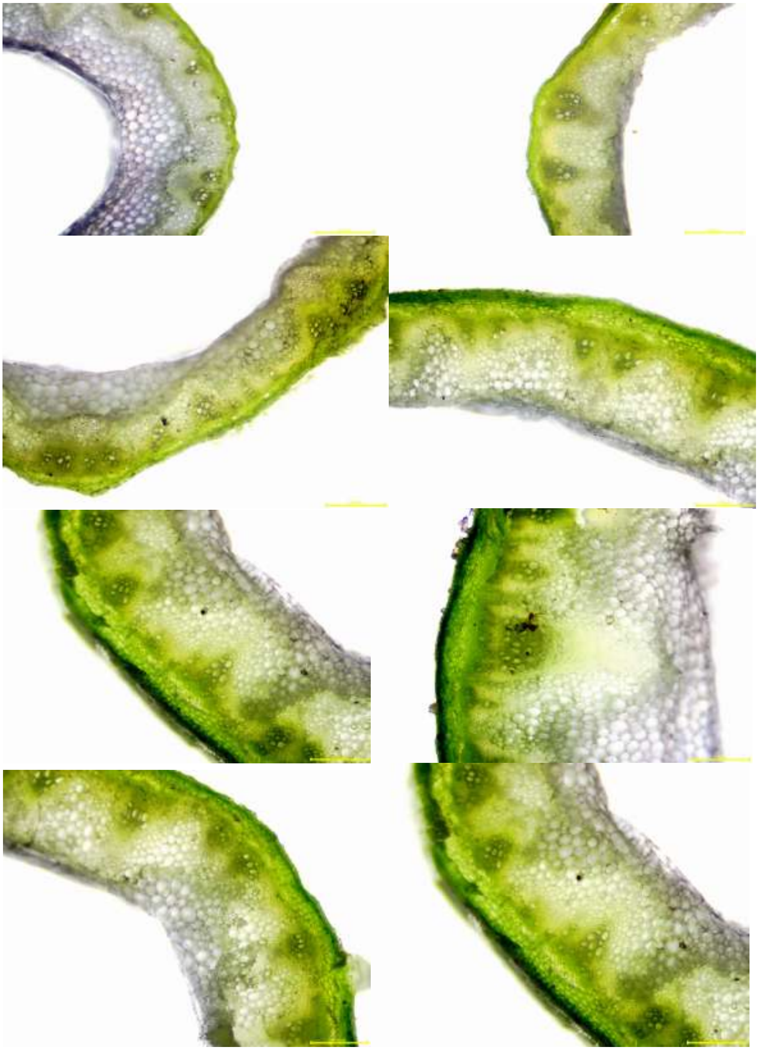


Figure 1.25b – Anatomical structure of oil radish stem walls during the flowering phase (BBCH 54–60) (cross section)

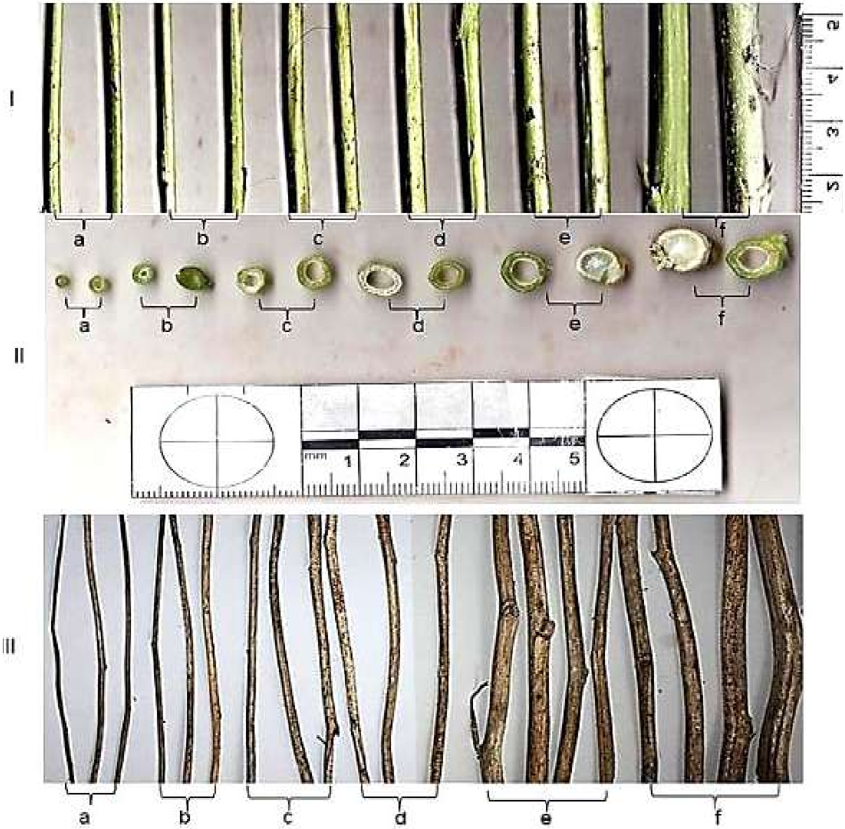


Figure 1.26 – Dynamic series of stem diameter at the base within the analyzed array of pre-sowing design of oilseed radishcenosis, 2019 (I – stems at the green pod stage of BBCH (62–65); II – cross-section of the stem at the base for the green pod phase (BBCH 62–65); III – stems for the phenological phase of the brown pod (BBCH 84–87); typical plant stems and itsdiameter cross-sections at the base against the background of $N_{90}P_{90}K_{90}$ application at the seeding rate (million germinating seeds ha^{-1}): row sowing a –4.0; b –3.0; c –2.0; wide-row sowing: d –1.5; e –1.0; f –0.5

The height of the stem of oil radish reaches its maximum value during the period of full flowering – fruiting. The value of this indicator can vary from 35 to 140 cm and depends on the complex of soil and climatic conditions, sowing time, varietal characteristics and fertilization (Shcherbakov, 2000). Oil radish is characterized by the ability to bloom very early, under certain conditions – the plant blooms at a stem height of 25–30 cm, and in some cases even at 12–18 cm, which plays an important role in the formation of such an indicator as reproductive effort (Tsytsiura, 2019).

The leaves of the middle part of the plant are lyre-shaped and peri-septate, and the upper part is lyre-lobed (Tsytsiura, 2020a. Figure 1.27), with certain patterns in venation, mesophyll thickness, and stomatal apparatus tropism (Figure 1.28, 1.28 (a–c)) with intense pubescence, especially in the early stages of formation and growth. The length and width of leaves and their morphology varies widely, depending on a wide range of factors from the level of mineral nutrition to water consumption conditions during the growing season (Tsytsiura, 2020a). The number of leaves per plant is a highly variable trait and ranges from 6 to 15 at a particular developmental stage. In the southern regions, when growing oilseed radish, the number of leaves is less than 6 to 9, in the northern regions the number of leaves can be higher than 12 during certain periods of the plant's vegetation. Thus, the leafiness of oilseed radish depends on the growing conditions. The share of leaves in the northern latitudes with optimal moisture accounts for 60–75% or more. As oilseed radish moves southward, the share decreases to 25–50% and even 15–20% (Tsytsiura, 2020a). Oilseed radish has a high potential for the formation of an assimilation surface from 150 thousand m^2 per hectare to 25 thousand m^2 per hectare (Krivitskyi, 1986; Radchenko, 2009; Drabyk, 2011; Kozlenko, 2011). The area of its leaf apparatus, as well as that of any agricultural crop, is determined by weather conditions, mineral nutrition, methods and timing of sowing, varietal characteristics and has a maximum expression from the budding phase to the flowering phase with a subsequent decrease due to the death of some leaves during fruiting (Kozlenko, 2011).

Figure 1.27 – Variability of leaf shape of Zhuravka oil radish plants (top position – 2012, bottom position – 2010 (leaves characteristic of the upper part of plants 9 – 25 are lyriform–lobed, middle 1 – 4 – lyriform–peripinnate, lower 5 – 8 – peripinnate)

а б в

Figure 1.28 – Venation pattern of oil radish leaves of 'Zhuravka' variety (2010), which obeys Zelensky's law regarding the number of conductive bundles per unit area of the leaf with changes in the tier of their placement (a, b, c – respectively, leaves of the lower, middle and upper tier)

Figure 1.28a – Scanned assimilation surface of a typical oilseed radish plant at a sowing rate of 0.5 million seeds ha^{-1} of similar seeds in the background with $N_{60}P_{60}K_{60}$ (2 cm^2 black marker square)

Figure 1.28b – Scanned assimilation surface of 6 typical oilseed radish plants at a sowing rate of 3.0 million seeds/ha of similar seeds in the background with $N_{60}P_{60}K_{60}$ (2 cm² black marker square)

Figure 1.28c – A number of morphotypes of oilseed radish leaves of different layers of placement

Figure 1.29 – Character of pubescence of different parts of oil radish variety Zhuravka

The highest fodder productivity of oil radish was observed at the presence of 40-60 thousand m^2/ha of leaf area in the flowering phase (Krivitsky, 1986; Rakhmetov and Kozlenko, 2008).

There is little literature on the biology of oil radish flowering. It is characterized by the fact that the differentiation of the growth cone begins in the phase of two true leaves. The second-order growth cone is formed, i.e. the growth points of the rudimentary flowers. The intensity of the second-order growth cone formation process determines the potential number of flowers in the future inflorescence. This process is very extended in time. It does not decay to the same extent as in other crops, such as cereals, due to the transition of the most developed inflorescence flowers to further stages of organogenesis. Significant heterogeneity of the emerging inflorescence as the flowers develop occurs in the early stages of organogenesis and persists until the seeds ripen.

Before flowering, the inflorescence is relatively compact and can be divided into separate lobes. Each such lobe is the future inflorescence, i.e. a peduncle with more or less flowers is formed on each lobe.

The central lobe of the inflorescence has undifferentiated flowers, and the most developed ones are located on the periphery. During the flowering period, when the peduncles are elongated and the inflorescence acquires the appearance of a brush, the most developed peripheral flowers are at the same stage of organogenesis. The number of inflorescence lobes before flowering mainly determines the number of flowers on the main axis. Peduncles in oil radish are often formed from axillary buds. Axillary inflorescences, like apical inflorescences, have several lobes and with their development the plant acquires the characteristic appearance of a branched bush. But axillary buds do not always develop, especially in the axils of the lower leaves.

Flower formation begins with the formation of a meristematic tubercle (Figures 1.30–1.31), on which sepals are first laid, followed by stamens and pistils, and much later corolla petals. Before budding, the sepals close and cover the stamens and the pistil column. During this period, the formation and growth of corolla petals begins. In the budding phase, intensive growth of all flower organs is observed. At the beginning of budding, the length of the flower does not exceed 0.5–0.6 cm, and before flowering, the flower reaches 1.5–1.8 cm in length.

Figure 1.30 – Ontogeny of oil radish flower.
1 – the beginning of the laying of floral meristematic zones;
2 – flower formation; 3 – flowers before budding

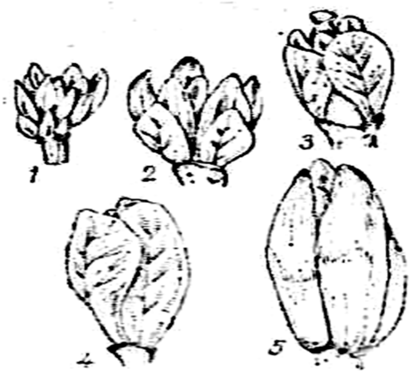
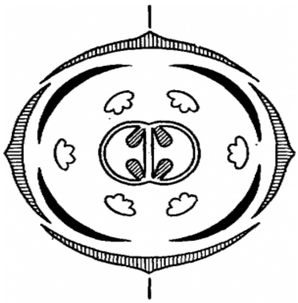


Figure 1.31 - Growth and development of an oil radish flower.
1 – before the beginning of budding (the beginning of the perianth petal mouth); 2 – at the beginning of budding;
3–4 – during the budding phase (further growth of perianth petals, stigma and anthers is observed); 5 – before flowering
(perianth petals completely cover the pistil and anthers)

Oilseed radish has no bracts. The flowers are bisexual, bilaterally symmetrical. Sepals 4, in 2 circles, the inner ones at the base with saccular outgrowths (Figures 1.32–1.40). Petals 4, with pronounced nails Stamens 6, 2 of them short and 4 long. At the base of the stamen filaments, in different numbers and arrangements, there are outgrowths of the flower axis. The arrangement of nectaries in oil radish is typical for the cruciferous family: the flowers contain two large arched nectaries located between the ovary and short stamens. They secrete nectar. There are also two small underdeveloped nectaries between the long stamens, but they do not secrete nectar.The ovary is upper, of 2 carpels, 2-nested with permanent placentation and a different number of anatropic or campylotropic seed embryos with 2 integuments. Column with a capitate or 2-lobed stigma.



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Flower formula: sepals (S), petals (P), stamens (St), anthers (A) $S_4P_4St_{4+2}A_1$

Figure 1.32 – Flower formula and structure of androecium and gynoecium in oil radish (type 3 flower)

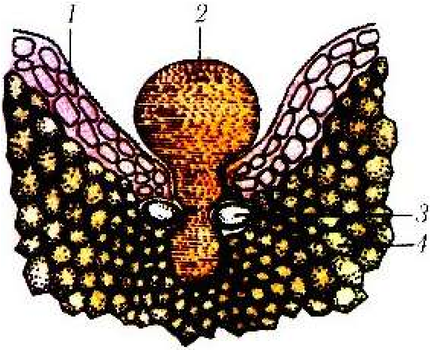

Figure 1.33 – Section of a typical nectarifer (Ponomareva and Deterleva, 1986) (1 – epidermal cells; 2 – nectar; 3 – cells that regulate the protrusion of a nectar drop; 4 – cells of nectar-bearing tissue)

Figure 1.34 – Longitudinal section of oil radish buds of Raduga variety at the beginning of budding (morphological rudiments of petals, stamens and pistils undifferentiated in color are visible)

Figure 1.35 – Transverse section of oil radish buds of the Raduga variety (upper position – at the beginning of budding, lower position – before flowering)

The flowers of oilseed radish are heterogeneous and both heterostyledonous and homostyledonous flowers are found in the population. There are 3 types of flowers: 1) the column is short, so that the stigma reaches only the lower edge of the anthers; 2) the stigma and anthers are at the same height; 3) the column is long and the stigma rises above the anthers. The 2nd and 3rd types of flowers usually prevail. According to Bazylev (1981), the number of flowers with long columns in the population of oil radish reaches 89%, according to other data (Radchenko, 2009) – no more than 53–55%. Recent studies have identified 2 more types of flowers in the oil radish population: 1) flowers with a well-developed pistil stigma, and stamens rising above the stigma only to the size of anthers; 2) stamens not equal in length (Figure 1.41).

Figure 1.36 – Oilseed radish buds of the Raduga variety (upper position – at the beginning of budding, lower position – before flowering)

Figure 1.37 – Longitudinal section of oil radish buds of 'Zhuravka' variety before bud opening (lower position – flower receptacle)

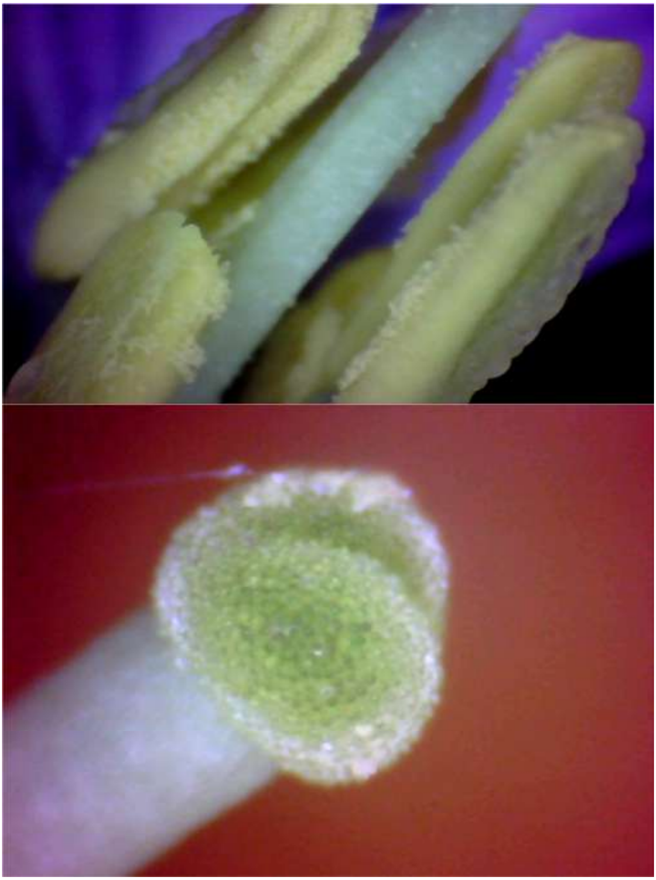

Figure 1.38 – Anthers and pistil with a column of oilseed radish flower of ‘Zhuravka’ variety

The flowering of oil radish begins with the main axis of the inflorescence, then the brushes on the second-order lateral shoots bloom (Figure 1.42–1.47). The clusters always bloom in an acropetal direction. In summer, the flowers open at 6–7 am. In autumn, this period shifts to 9–10 o’clock, and with a drop in temperature to 10 ºC, the flowering time shifts to a later time. The flowering time of one flower is 2–3 days and depends on the air temperature. In all types of flowers, anthers at the beginning of flowering are turned with their opening side to the stigma, and later they are angled outward, so that pollen does not fall on the stigma of this flower (Figures 1.47–1.49). Thus, the structure of the flower and the arrangement of the anthers before the pollen ripens makes self-pollination impossible and occurs in very rare cases.

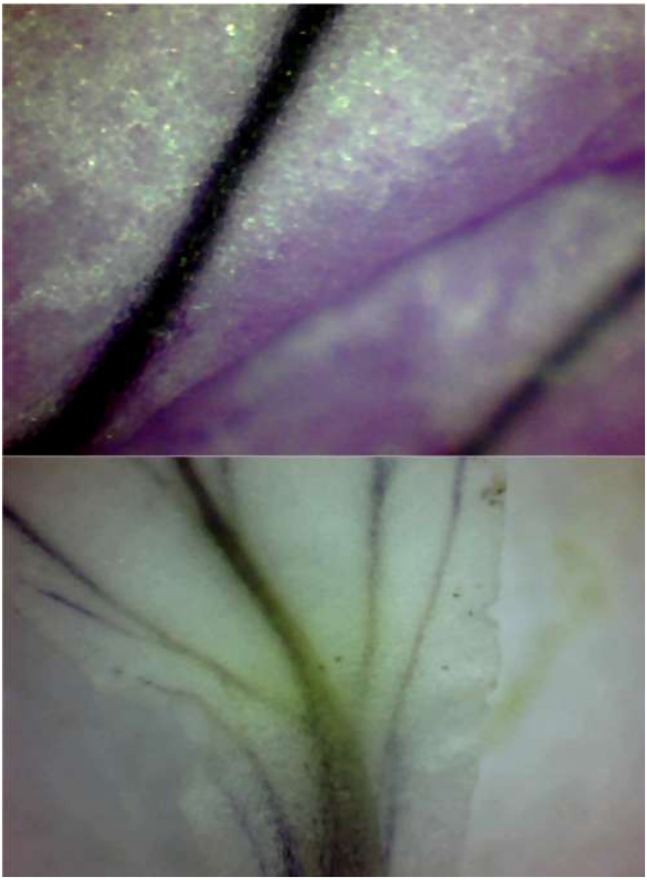

Figure 1.39 – Petals of oilseed radish flowers (top position – 'Raduga' variety, bottom position – 'Zhuravka' variety)

Figure 1.40 – The nature of pubescence of oil radish buds (magnification 200x)

The color of the flowers is one of the varietal traits and is mostly white, but pink, purple, and yellowish can also occur (Figures 1.46–1.47).

Oil radish, as mentioned earlier, has unique properties in terms of juvenile flowering, when the plant blooms at a stem height of 15–30 cm (Bazylev, 1981), and in some cases even at 10–15 cm (Kengbaev, 1986) (Figure 1.48). Such a flowering pattern is primarily associated with unfavorable hydrothermal regime of vegetation, especially under conditions of a sharp increase in the average daily temperature against the background of a prolonged soil moisture deficit. Under these conditions, oil radish plants develop slowly in terms of morphological traits (height, number of leaves, etc.) and undergo accelerated qualitative differentiation. That is why radish is able to bloom in this way during prolonged drought.

Moreover, it was noted that juvenile flowering is characteristic of 5-10% of plants. This fact plays an important role in the formation of such an indicator as reproductive effort (RE (Kengbaev, 1986a), which affects the level of seed productivity of the crop and its adaptive potential – oil radish is able to form a certain minimum of seeds even under the most unfavorable conditions of its growth and development. Thus, according to H. F. Batyrov (Kengbaev, 1983), in the conditions of the Republic of Uzbekistan, oilseed radish in a short growing season of 20–25 days, due to the intensive increase in temperatures in March-May for the conditions of Central Asia, formed inflorescences on 8–12% of plants and provided seed productivity at the level of 35–50 kg ha^{-1}.

Figure 1.41 – Pistil of oilseed radish flower pistil of different types by the height of the stigma (top position – 'Zhuravka' variety, bottom position – 'Raduga' variety)

Figure 1.42 – The beginning of flowering of the main axis of the inflorescence in the variety Rainbow (upper position). Differentiation in the flowering of the main axis with formed pods and axes of the following orders (formed flowers and buds) (lower position)

Figure 1.43 – The beginning of the opening of an oil radish flower of the Zhuravka variety

Figure 1.44 – Flower of oil radish variety Zhuravka (upper position – during the opening period, lower position – during the period of active flowering)

Figure 1.45 – Oilseed radish flowers of different varieties (top position – Raduga variety, middle position – 'Zhuravka' variety, bottom position – Compass variety)

Figure 1.46 – Inflorescence of oil radish variety 'Raduga' (the variety is characterized by white or pale yellow flowers)

Figure 1.47 – Inflorescences of oil radish variety 'Zhuravka' (the variety is characterized by pale purple or pink-purple flowers)

Figure 1.48 – "Juvenile" type of flowering of oil radish under unfavorable hydrothermal conditions of vegetation

The formation of flowers and the number of fruits set is determined by both environmental factors and the nature of the plant itself. It has also been found that with prolonged cultivation of oil radish in northern conditions, the pubescence of its flowers is significantly reduced.

The time of flower opening, as well as the order of inflorescence flowering, can change under the influence of stress factors (a sharp increase in temperature, a sharp decrease in air humidity, etc.) (Dudka, 1993).

Oil radish can be well pollinated both by insects and wind (Figure 1.49). 1 to 2 days before opening, the flower is ready for fertilization. Therefore, researchers involved in oil radish breeding need to take this feature of its development into account.

The future seed productivity of oil radish may be determined by the nature and intensity of inflorescence flowering and the reproductive efforts of the plant itself (Tsytsiura, 2021), which is an under-studied issue for the conditions of the Ukrainian Forest-Steppe. The formation of generative organs is extended in time. The intensity of their formation is determined by the level of nitrogen nutrition, temperature conditions during flowering, and sowing dates (Kryvytskyi, 1986).

Figure 1.49 – Insect pollinators on oilseed radish crops

The fruit is a thickened pod with a sharp tip, 4-8 cm long and 1-1.5 cm in diameter, convex, without bands with thickened walls. The pods of oil radish have different shapes and sizes within the inflorescence depending on their placement on the branches of the corresponding order (Tsytsiura, 2022, Figures 1.50-1.55). This fact is important for understanding the patterns of seed formation within the inflorescence and the formation of seed productivity of the crop. A positive characteristic in the structure of the fruit is its strength, high mechanical resistance to cracking, which prevents seed shedding and its preservation from the adverse effects of external factors, but this feature is an obstacle to effective threshing. In addition, the inside of the pods contains a large amount of parenchymal tissue with high hygroscopicity, which creates additional difficulties when harvesting in rainy weather, which are solved in production by desiccation (Sedlyar, 1984). Due to their different phenology within the inflorescence, pods ripening is also uneven, especially in rainy weather during the ripening period. As a rule, the pods of the main axis of the inflorescence ripen first, and after a while the pods of the second-order axes ripen. That is why double threshing is practiced on radish crops or desiccation is used in the middle of the yellow-green pod phase. Desiccation allows to accelerate the process of pods ripening in different locations within the inflorescence and to obtain an increase in seed yield of 0.9–1.3 c ha^{-1} (Dorofeev, 2010).

Figure 1.50 – Morphotypes of oil radish pods

Figure 1.51 – Variation series of oil radish pods of Zhuravka variety within one inflorescence at the fruiting stage (green pod stage)

Figure 1.51a – Variable series of morphotypes of oilseed radish pods

Figure 1.51b – Variable series of morphotypes of oilseed radish pods

Figure 1.52 – Oilseed radish pod (longitudinal and transverse views) during its formation

Figure 1.53 – Oilseed radish seed in the developed "parenchymal sleeve" of the pod at the stage of waxy ripeness (magnification 200x)

Figure 1.54a – Character of the morphological structure of the walls of the pod of oil radish variety 'Zhuravka' at the stage of green pod and its transverse section at the stage of milky-wax ripeness of seeds

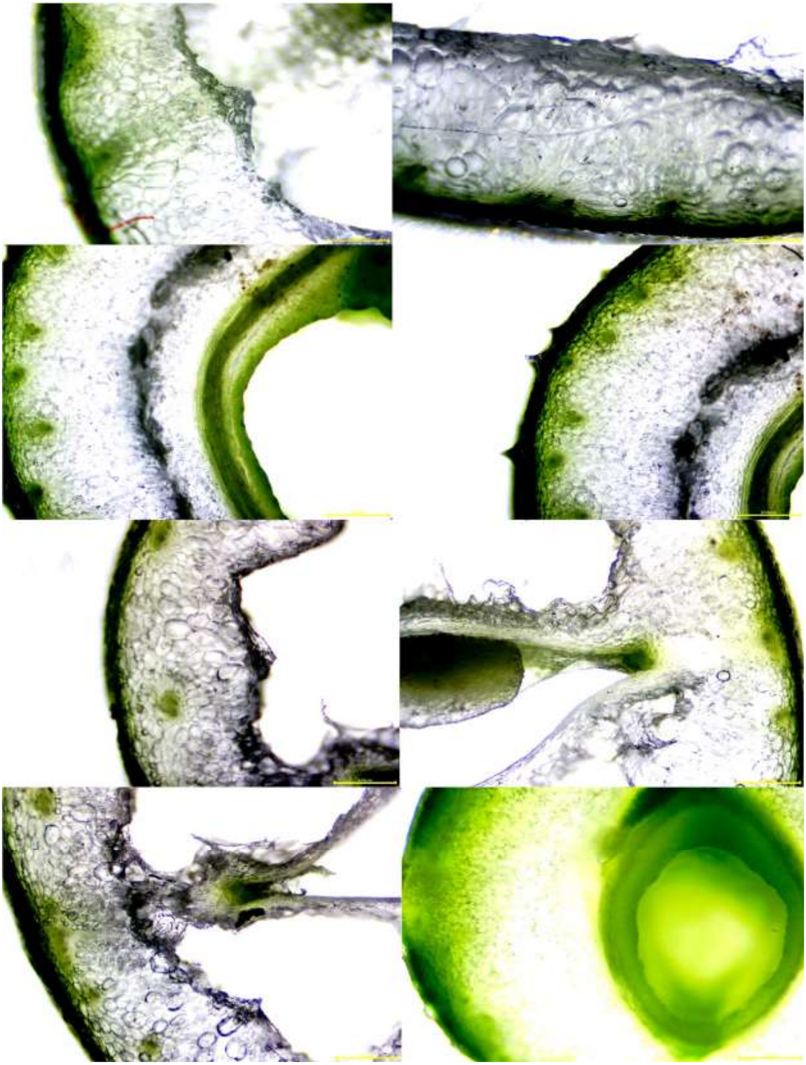

Figure 1.54b – Character of the morphological structure of the walls of the pod of oil radish variety 'Zhuravka' at the stage of green pod and its transverse section at the stage of milky-wax ripeness of seeds

An oilseed radish pod contains 3 to 12 seeds (Figure 1.56), which are bright brown in color (when fully ripe). The number of seeds in a pod is determined by such factors as sowing time (early sowing has higher total and individual seed productivity (Sedlyar, 1984)), as well as weather conditions during the period from budding to the beginning of flowering of the lateral branches of the second inflorescence (Krivoruchenko, 1995).

Figure 1.55 – Spatial arrangement of oilseed radish seeds in the pod

Figure 1.56 – Variation in the number of seeds per pod of oil radish variety 'Zhuravka'

The weight of 1000 seeds varies widely from 7 to 13 g and depends on growing conditions and harvesting time (Sedlyar, 1984). This indicator in oil radish has a high variability with a value for the main shoot of the inflorescence in the range of 7–13 g, lateral shoots of the second order of medium placement 6–9 g, lower placement 5–7 g. Tetraploidy increases the weight of 1000 seeds, as for example in the oil radish variety Tambovchanka, where this index is 1.5–3 g higher than in diploid varieties (Bolshov and Karabin, 1988, Figures 1.57–1.61).

Figure 1.57 – Stages of oilseed radish seed formation in 'Zhuravka' variety (electronic magnification 200x) (sequentially from left to right, top to bottom: seed formation: in the early milk ripeness phase; at the end of the milk ripeness phase; in the milk-wax ripeness phase; in the wax ripeness phase; in the full ripeness phase)

Oilseed radish seeds have no endosperm. The embryo (Figure 1.58) consists of two formed cotyledons with a germinal root and a growth point symmetrically located between them.

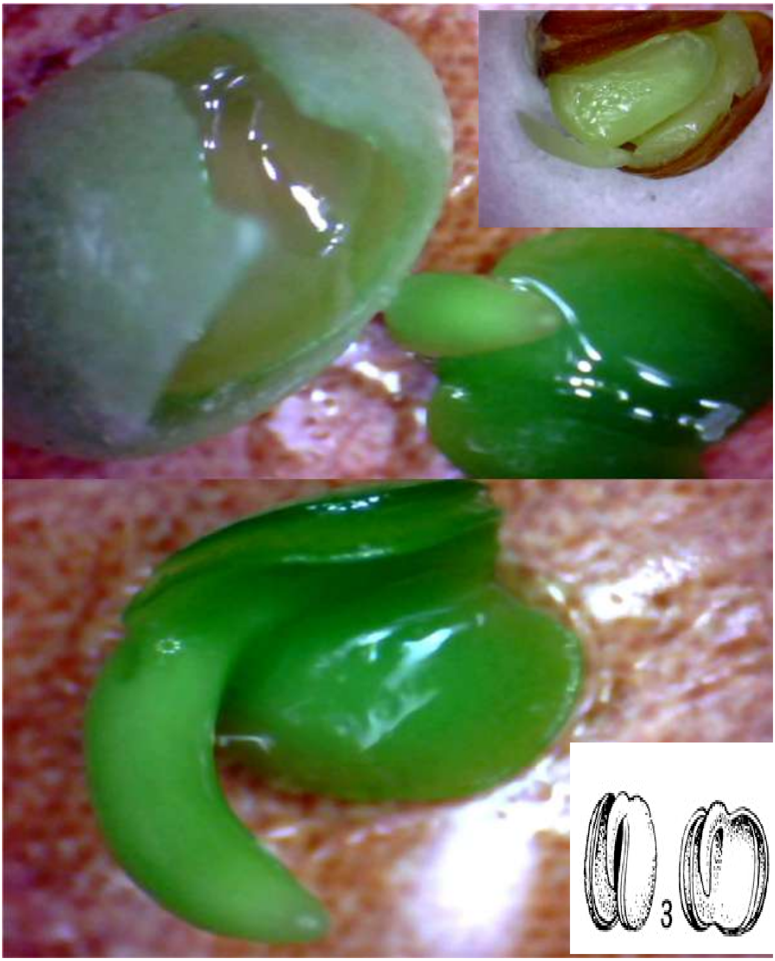

Figure 1.58 – Oilseed radish seed embryo (type 3 of embryo root placement – folded; in the upper right corner – color of the embryo at the stage of waxy ripeness of the seed)

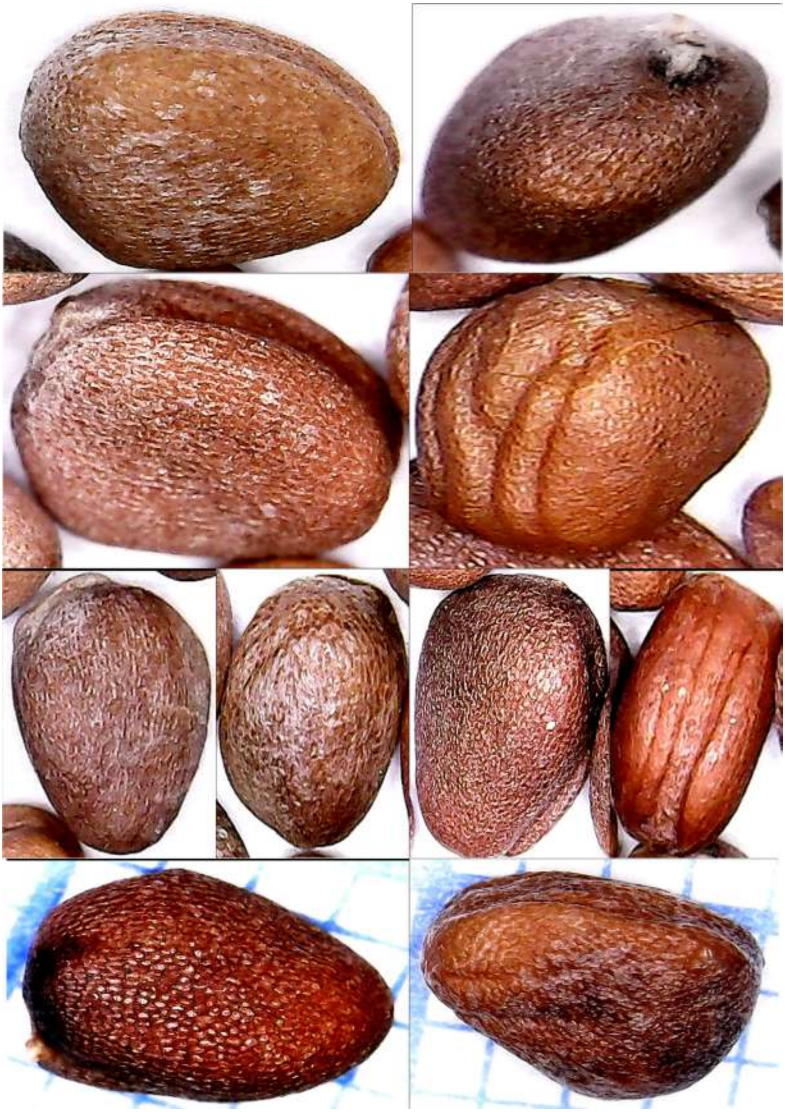

Figure 1.59 – Oilseed radish seeds of Zhuravka variety (magnification 200x)

Figure 1.60 – Transverse section of an oil radish seed (top position of 'Zhuravka' variety, bottom position of 'Raduga' variety)

Figure 1.61 – Seed surface at milky ripeness (top position) and at full ripeness (bottom position) (300 x magnification)

1.3. Agrotechnological potential of oilseed radish

Changes in agricultural production vectors, crop structure, and new approaches to realizing the effective potential of crops require the use of highly productive fodder crops with stable adaptive properties and high feed value (Likhochvor, 2010).

Interest in less common fodder crops emerged in the late 80s of the last century. This group of crops was considered as a source of feed protein, which have a wide range of adaptive properties and can be effectively cultivated in different soil and climatic zones (Radchenko, 2009).

The presented results indicate the economic prospects and high plasticity and adaptability of oil radish as a fodder crop grown from the Arctic Circle to the arid zones of Central Asia, demonstrating high levels of both fodder and seed productivity (Figure , Tables 1.2–1.5).

Table 1.2

Harvest of oilseed radish leaf mass and seeds in different geographical regions for the period 1950–2014, t ha^{-1} (summarized and grouped by Tsytsiura and Tsytsiura, 2015))

Geographical area	Leaf and stem mass	Seeds
Poland	300–700	15–22
Germany	300–750	16–24
France	250–480	12–16
Northern regions of the USA	180–370	8–20
Lithuania, Estonia, Latvia, Belarus	300–450	9–13
Moldova	250–400	8–15
Hungary, Romania	300–450	10–20
Ukraine:		
– northern regions	300–700	10–16
– central regions	300–520	12–20
– southern regions	220–350	11–18
Kazakhstan	200–340	12–15
Uzbekistan, Tajikistan	140–200	3–7
Northern regions of the Eurasian continent	250–600	9–12.5
Extreme northern regions of the Eurasian continent	125–200	3–7
Northwestern regions of the Eurasian continent	170–310	9–12
Central regions of the Eurasian continent	400–600	5.5–10
Southern regions of the Eurasian continent	204–400	5.2–12
Far Eastern regions of the Eurasian continent	180–314	3.5–8

The first evidence of the effectiveness of oil radish use in the territory of former Russia dates back to the early nineteenth century and dates from 1802 to 1811. Some researchers emphasized the expediency of its cultivation and the possibility of industrial processing of seeds to obtain vegetable oil (Batalin, 1879).

In the review articles of Kalynovskyi in the period 1880–1892, he highly appreciated oil radish as a fodder crop with a high degree of cattle consumption. The chemical analysis of its leaf-stem mass carried out in 1893 by Schultz (one of the first) showed a content of up to 12.58% protein, 2.52% fat and 11.78% ash. Already at that time, it was recommended to use it as a green manure, especially on soils with heavy mechanical composition, and its positive effect on the yield of winter cereals and potatoes was noted (Tsytsiura and Tsytsiura, 2015).

Table 1.3

Average annual productivity of annual fodder crops in the Northwest region of the Eurasian continent (average long-term data) (Kapustin, 2012)

Cultures	Green mass yield, t ha^{-1}	Dry matter harvest, t ha^{-1}	Crude protein harvest, t ha^{-1}
Corn	37.4	5.70	0.38
Sunflower	59.8	7.74	0.99
Crimson amaranth	27.4	3.47	0.49
Panicle amaranth	24.1	3.19	0.47
Fodder beans	37.3	6.10	1.20
Small mallow	28.5	5.46	0.73
Yellow lupine	18.5	2.48	0.56
White lupine	13.2	3.17	0.55
Spring rape	23.6	3.14	0.65
White mustard	25.5	4.52	0.76
Oilseed radish	27.7	5.13	0.97
Ragweed	20.3	3.61	0.68
Peas + oats (control)	24.0	4.26	0.62
LSD_{05}	2.7	0.33	0.05

Table 1.4

Productivity of different fodder crops under different cultivation technologies on sod-podzolic soils of the Non-Chernozem zone (Kapustin, 2012)

Agricultural crops	Technology	Yield of aboveground mass, t ha^{-1}	Weight of post-harvest and root residues, t ha^{-1} (WPR)	Above-ground mass + WPR, t ha^{-1}
White sweet clover	Extensive	2.6	3.1	5.7
	Normal	3.8	4.3	7.1
	Intensive	4.5	5.2	9.7
Meadow clover	Extensive	2.9	4.4	7.3
	Normal	4.0	4.5	8.5
	Intensive	5.1	6.1	11.2
White mustard	Extensive	2.5	2.8	5.3
	Normal	3.7	4.4	8.1
	Intensive	4.4	5.1	9.5
Oilseed radish	Extensive	4.0	5.6	9.6
	Normal	5.7	6.6	12.3
	Intensive	7.9	9.7	17.6

A valuable property of oil radish as a fodder crop is the ability to produce 1–3 mowings of flocks, which allows to obtain additional yields of leaf mass in years of sufficient moisture, and two mowings can be equivalent in productivity (Uteusch, 1991).

Today, oil radish is considered as a means of reviving the fertility of depleted soils, especially as a substitute for organic fertilizers for plowing biomass and a highly effective field phytosanitary (Shuvar, 1994).

Many sources emphasize the value of oil radish as a protein fodder crop. According to Uteusch (1991), at fodder ripeness, the aboveground mass contains (% of absolutely dry matter) 22–23% protein, 24–25% BER, including 7–8% sugars, 5–6% lipids, 25–29% fiber, and 17–18% ash. In 100 kg of weight – 16 feed units with a content of 198 g of digestible protein. However, the sugars in the radish leaf mass are in a highly insoluble form. That is why it is recommended to grow oilseed radish in mixtures with oats, corn and other crops. This crop is also valuable for the amino acid composition of the leaf mass, the quality of which is determined by hydrothermal conditions of vegetation – under dry conditions, the protein content of the green mass increases (Table 1.6).

Table 1.5

Characteristics of annual fodder grasses that are promising for cultivation in Ukraine (Rakhmetov, 2000)

Crop	Sowing date	Seeding rate, kg ha^{-1}	Depth of tillage, cm	Row spacing, cm	Harvesting time (rosette phase)	Yield, t ha^{-1}	Application	Crop form
Winter melilot	August 20–30	6–8	2–3	15–30	Budding – ripening of seeds	25–30	Feed, green manure, biofuel	winter
Oilseed radish	Early spring to the second decade of August	10 – 30 depending on the method and time of sowing	2–3	15–60	Budding – ripening of seeds	25–40	Fodder, green manure, biofuel, honey plant	spring
Small mallow	From early spring to the second decade of August	3–6	2–3	45	Budding – ripening of seeds	40–60	Fodder, green manure, biofuel, honey plant	spring
Amaranthus	I - II decade of May	1	1.5–2.5	45–70	Budding – ripening of seeds	35–50	Feed, food, decorative	spring

Table 1.6

Chemical composition of leaf and stem mass of oil radish variety 'Raduga' by stages of growth and development (Getman, 2007)

Phases of growth	Dry matter content, %	Content in dry matter, %				
		protein	cellulose	fat	Nitrogen-free extractives	ash
The beginning of flowering	11.8	24.4	21.2	3.6	35.4	15.4
Full flowering	12.6	20.8	23.0	2.8	37.6	15.8
Beginning of pod formation	15.2	16.4	28.1	2.8	36.4	16.3

Different parts of plants differ in chemical composition (Pirie, 1972). For example, according to Werner (1983), the most valuable part of the plant is the leaf (Table 1.7), and the quality of the leaf mass is closely correlated with the leafiness of the plant. The leaves contain the bulk of ash, calcium, protein and fat (Table 1.8–1.10).

Table 1.7

Chemical composition and nutritional value of oilseed radish leaf mass in 1 kg (Getman, 2007)

Mowing phase	Moisture content, %	Metabolic energy, MJ	Feed units.	Protein		Sugar, g	Fat, g	Crude fiber, g	Calcium, g	Phosphorus, g	Carotene, mg
				crude	digestible						
Clean spring sowing											
Leaf and stem mass in the phase:											
budding	88.2	1.2	0.11	21	15.7	15	6.7	31.7	2.17	0.45	21
beginning of flowering	87.3	1.25	0.12	23.6	16.3	19.7	7.22	33.6	2.28	0.49	29
end of flowering	84.6	1.39	0.14	24.1	16.6	22.1	7.01	37.9	2.22	0.50	23
In dry matter	–	8.64	0.91	158	108	146	45.5	246	14.4	3.25	252
Clean post-harvest sowing											
Beginning of flowering (per wet weight)	89.3	1.13	0.10	19.5	14.9	18	5.9	29.2	1.79	0.41	28
in dry matter	–	10.6	0.94	182	139	168	55	272	16.7	3.8	261
Full flowering (per wet weight)	86.7	1.32	0.13	21.5	16.1	21.3	7.01	36.9	2.02	0.44	25
in dry matter	–	9.92	0.98	162	121	160	52.7	277	15.2	3.33	188

Table 1.8

Comparative chemical composition and nutritional value of green fodder of cruciferous crops in different phases of vegetation (Getman, 2007)

Cultures	Contained in 1 kg of absolutely dry matter								Carotene, mg/kg of natural feed
	Feed units	Metabolic energy, MJ	Crude protein, g	Crude fat, g	Crude fiber, g	Nitrogen-free extractive substances, g	Ca, г	P, г	
Flowering phase									
Winter rape	0.92	10.67	224.6	42.4	240.5	405.7	23.0	12.5	22.69
Spring rape	1.09	11.61	196.3	58.0	188.6	455.9	21.5	13.3	38.69
Oilseed radish	0.92	10.63	200.6	52.6	242.7	389.7	25.0	10.3	30.99
Winter melilot	0.93	10.74	217.5	52.1	236.6	400.4	19.8	11.2	24.23
White mustard	1.01	11.15	245.6	41.4	213.9	402.4	26.2	10.4	39.28
Flowering phase (mass is tied up to a humidity of 70–75%)									
Winter rape	0.91	10.60	219.5	41.0	244.7	393.6	22.6	13.1	23.90
Spring rape	1.03	11.30	194.4	53.5	215.5	412.9	22.0	13.2	44.24
Oilseed radish	0.91	10.59	199.7	52.5	245.2	409.2	24.6	10.3	34.21
Winter melilot	0.84	10.20	200.2	50.1	266.4	393.0	19.2	10.5	24.95
White mustard	0.87	10.97	339.6	40.1	224.0	393.8	25.2	10.5	44.80
End of flowering – beginning of fruit formation									
Winter rape	0.86	10.28	186.3	34.2	262.0	419.4	10.5	5.3	25.43
Spring rape	0.89	10.47	196.1	41.5	251.8	409.6	19.5	7.7	35.98
Oilseed radish	0.93	10.70	180.0	48.0	239.1	451.5	19.7	4.5	28.95
Winter melilot	0.88	10.44	188.8	41.2	253.5	421.0	10.4	6.7	26.14
White mustard	0.91	10.61	193.8	46.4	244.0	419.6	12.5	8.0	35.28

Table 1.9

Chemical composition and nutritional value of oil radish leaf mass, % (summer sowing) (Uteusch, 1991)

Stages of organogenesis	Crude protein	Crude fat	Crude ash	Crude fiber	Nitrogen-free extractive substances	Sugars + starch*	Feed units	Crude protein per 1 feed unit
The budding of the flower	25.9	2.3	18.5	18.2	35.1	3.34	0.87	29.7
The beginning of flowering	22.0	1.6	20.6	26.1	29.7	4.12	0.78	28.2
Full flowering	18.2	1.9	15.3	27.1	37.6	6.06	0.85	21.41
Pod formation	18.0	1.8	16.1	26.8	37.3	7.00	0.84	21.42

* This group of nutrients improves microbiological processes in the rumen, the level of volatile fatty acid formation and their percentage. The level of easily digestible carbohydrates in diets is regulated by the ratio to digestible protein. The optimal ratio of sugar to digestible protein in winter in the diets of lactating cows is in the range of 0.8–1.0:1.2 (in oil radish, this ratio is 0.25–0.50:1 with a maximum in the interphase period of full flowering – green pod). Lack of sugar in feed reduces microbial protein synthesis, negatively affects fiber digestion and carotene absorption.

Table 1.10

Chemical composition of vegetative organs of oil radish plants in % on absolute dry matter (Werner, 1983)

Vegetative organs of plants	Ash	Protein	Fiber	Fat	Calcium	Phosphorus
Leaves	18.5	15.7	18.5	4.1	3.35	0.35
Stems	9.5	10.3	30.9	2.0	0.83	0.38
Pods	6.2	13.7	17.1	2.9	0.71	0.46

In addition, oil radish seeds are valuable for their protein content (Table 1.11–1.12).

During the growing season, the chromic composition of plants changes (Samokhin, 1976): At the beginning of flowering, the protein content in the leaf mass of oilseed radish reached 24.44 %, and at the end of the growing season it decreased to 11.44 %. The ash content of its mass in the budding phase was 24.15 %, by the beginning of mass flowering it decreased to 17.3–18.31 %, and during the fruiting period – 16.7–17.8 %. According to various estimates, 100 kg of its leaf-stem mass contains from 12 to 18 k.o., which accounts for 120–220 g of digestible protein.

Table 1.11

Crude protein content and yield from seeds of spring oilseeds depending on species characteristics (Kozlenko, 2011)

Crops	Protein content, %.	Protein yield, kg ha^{-1}
Spring rape	20.69	562.11
Spring melilot	18.52	298.12
White mustard	24.35	625.68
Grey mustard	23.91	530.75
Oilseed radish	21.28	427.73
Spring camelina	25.00	575.72
Safflowe	11.10	207.21
Oil flax	22.81	536.81

Table 1.12

Amino acid composition of leaf and stem mass of oil radish on an unfertilized background depending on the regime of vegetation moisture (Werner, 1983)

Amino acid	Content in absolutely dry matter	
	in relatively dry years	into normal moisture content
Lysine	1.17 – 1.36	0.75 – 0.92
Histidine	0.43 – 0.57	0.26 – 0.33
Arginine	0.84 – 0.92	0.60 – 0.74
Asparagine	1.66 – 1.72	1.14 – 1.32
Threonine	0.81 – 0.94	0.61 – 0.74
Serine	0.83 – 0.95	0.58 – 0.72
Glutamine	2.41 – 2.75	1.91 – 2.15
Glycine	0.78 – 0.86	0.61 – 0.72
Valine	0.97 –1.12	0.73 – 0.86
Isoleucine	0.72 – 0.81	0.46 – 0.58
Leucine	1.39 – 1.48	0.94 – 1.16
Tyrosine	0.61 – 0.81	0.40 – 0.55
Phenylalanine	0.88 – 0.97	0.63 – 0.78
Alanine	0.90 –1.03	0.71 – 0.82

In the studies of T. D. Mosin (1989) it was found that the growth of dry matter in oil radish continues steadily for 20-30 days after the onset of the flowering phase. At the same time, the fodder value of oil radish leaf mass had maximum values in the period of the beginning of flowering – full flowering, but there was a steady tendency to decrease the provision of a feed unit with digestible protein (Tables 1.13–1.14). Based on these statements, the mowing maturity of oil radish is considered in the plane of the beginning of flowering – the beginning of fruiting to maintain a positive combination of chemical composition and yield of leaf mass.

Table 1.13

Dependence of the quality of oilseed radish leaf mass on the harvesting time (Mukhina, 1980)

Harvesting period	Dry matter, %	Content per 1 kg of absolutely dry matter				Provision 1 k. unit of digestible protein, g
		phos-phorus, g	potassium, г	calcium, g	feed units, kg	
The beginning of flowering	9.4	4.62	48.1	25.1	0.86	276
Full flowering	11.4	3.49	37.3	22.0	0.83	234
The beginning of fruiting	11.9	3.33	32.4	20.0	0.83	209
The middle of fruiting	13.9	2.41	28.6	18.8	0.83	181
End of fruiting	15.4	2.68	32.0	18.7	0.80	167

According to Bakhmat (1993), 1 kg of dry matter of oil radish contains up to 50 g of sugars (146–160 g according to Podobed (2009)), which allows the crop to be used as a lactic fodder. Moreover, Shlapunov (1987) noted that the sugar content in the leaf mass tends to increase from 7–12 % in the budding phase to 13–16 % in the fruiting phase and 16–19 % in the seed ripening phase, which plays a role in determining the optimal phase for silage crops – the phase of the beginning of fruiting. The leaf mass of oil radish is also rich in potassium, calcium, trace elements and vitamins. The content of copper is 2.2–2.5 mg per 1 kg of absolutely dry matter, zinc 20–35 mg, manganese 20–40, molybdenum 0.3, cobalt 0.10 mg (Bitov, 2001). The content of ascorbic acid in the budding phase per 100 g of dry matter is 70–80 mg (1000–1050 g per 100 g of dry matter), and during the fruiting period, respectively, 63 and 525. The carotene content ranges from 4 to 5 mg per 100 g of dry matter (Podobed, 2009). In the research of the Department of Agriculture (during two rotations of four-field grain and fallow crop rotation, 1996–2003), oil radish was grown in occupied pairs for fodder, and in green manure pairs it was used as a green fertilizer. According to the results of chemical analysis of its leaf mass, it was found that during the flowering period, 1 kg of green mass of oil radish contains (in terms of dry matter) 19.7 crude protein, 3.0 fat, 18.04 ash, 1.95 calcium and 0.33 phosphorus. The culture is characterized by a high content of macro- and microelements (Table 1.15).

Table 1.14

Protein value of oil radish leaf mass depending on the harvesting period, in % on absolutely dry matter (Shlapunov, 1987)

Budding		Full flowering		Fruiting		Wax ripeness of seeds	
crude protein	pure protein	crude protein	pure protein	crude protein	pure protein	crude protein	pure protein
26.4 – 28.9	20 – 23.7	15.4 – 21.7	14.2 – 15.9	14.1 – 15.0	12.1 – 13.4	12.1 – 12.7	7.7 – 10.6*

* – range of values within the annual fluctuations of the indicator.

Table 1.15

Chemical composition of oil radish leaf mass by content of of macro- and microelements (Concept of the targeted comprehensive research program of the National Academy of Sciences of Ukraine, 2018)

Indicator	Content
Macroelementi, g kg^{-1}	
Potassium	14.50
Sodium	0.90
Magnesium	2.09
Sulfur	6.02
Chlorine	4.00
Trace elements, mg kg^{-1}	
Iron	149.8
Manganese	62.0
Copper	6.0
Zinc	36.0
Cobalt	0.90

Today, in European countries, oil radish is firmly established as a component of the fodder crop group in Poland, Germany (mainly East Prussia, Neumark), the Southern part of Great Britain, South-Eastern Romania, the Czech Republic and Slovakia, and even in Spain. In these countries, oil radish is mainly grown together with seradella and other legumes for fodder and as the main component in organic farming and production of environmentally friendly products (Tsytsiura, 2013). Another direction of its use has clearly emerged to produce vegetable oil, which is used for biofuel production and is close to rapeseed oil in a number of characteristics (Tsytsiura and Tsytsiura, 2011). In European countries, this area is actively developed by Germany, Poland, and the UK, where varieties with high oil content in seeds are being created. It should also be noted that oil radish forms a large phytomass, which in turn can be used as green manure and for fermentation to produce biogas. Between 2000 and 2020, its area in Europe and the United States (northern states) almost tripled compared to 1990. In particular, the Landkom company is actively engaged in growing oil radish in Europe and South Africa. In the United States, the center for the study of vegetable oil from radish is the state of Georgia (UGA College of Agricultural and Environmental Sciences). The research of scientists at this institution notes that oil radish is an extremely promising non-food crop for the production of alternative fuels. The seeds of this crop contain 40–45% of vegetable oil, which is similar in chemical composition to rapeseed oil and has a wide range of economic uses, which in turn makes it an excellent candidate for the biodiesel market (Sharon, 2020). Thus, Shpaar (1999) notes that the technical direction of its oil use is determined by the content of simple unsaturated fatty acids (in % of the total fatty acid content – aicosene (8–11%) oleic (23–36 %), erucic (9–30 %)), high content of saturated oleic acid (4–6 %), low content of multiple unsaturated linoleic (10–18 %) and linolenic (11–17 %) fatty acids. However, the high content of glucosinolates up to 160–180 μmol/g makes it difficult to use oil radish cake and oil in animal feeding.

It should be noted that in Ukraine, at present, industrial processing of oil radish according to the “pressing – extraction” scheme for the production of technical oil is complicated by the lack of regulatory and technical documentation (DSTU, TU, etc.) for oil and meal made from it.

It should not be forgotten that oil radish is a good honey plant with a multi-term use from June to September. The productivity of honey harvesting is 50-70 kg/ha (Tsytsiura and Tsytsiura, 2015).

It is widely used in biological and organic farming systems. The crop is used as a biological ameliorator in crop rotations with potatoes to increase soil organic matter supply and reduce weed infestation of field crops of a wide range of uses (Tsytsiura and Tsytsiura, 2015).

According to Likhochvor (2008), to control the number of nematodes in the links of crop rotations where sugar beets and rapeseed are grown, it is important to grow nematode-resistant varieties of oil radish both in the main crop and in post-harvest crops. The author notes that oil radish varieties have been created that are suitable for biological destruction of the nematode in the soil. These are varieties of foreign selection Colonel, Pegletta, Matador and domestic selection Zhuravka. These varieties can be used as intermediate provocative crops. Polish researchers (Nowakowski, 1996) found that the reduction in the number of nematodes in the cultivation of nematode-resistant radish varieties in post-harvest crops is 30–50%, namely in the Kolonel variety – 46%, Remonta – 42%, Adagio – 40%.

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CHAPTER 2. EFFICIENCY OF OIL RADISH IN THE SYSTEM OF SOIL BIOFUMIGATION TECHNOLOGIES

2.1. Cruciferous plant species in the system of biofumigation as an innovative technology for the rehabilitation of degraded soils

Clarkson et al. (2020) noted that the term 'biofumigation' was originally coined by J.A. Kirkegaard to describe the process of growing, macerating/incorporating certain Brassica or related species into the soil, leading to the release of isothiocyanate compounds (ITCs) through the hydrolysis of glucosinolate (GSL) compounds contained in the plant tissues (Kirkegaard et al., 1993). This can result in a suppressive effect on a range of soil borne pests and diseases. Since then, the term 'biofumigation' has been used rather loosely and incorrectly in some contexts, to describe any beneficial effects derived from the use of green manures, organic amendments and composts. In this mini-paper, biofumigation is considered in its strictest sense as referring to the use of glucosinolate-containing plant material with the intention of enabling ITC-mediated pest and disease suppression. Biofumigation could be considered as a 'natural' alternative to chemical fumigation and there is an analogy with the use of metam sodium which releases methyl-ITC, to control a variety of soilborne diseases.

Biofumigation is the suppression of soil pests, nematodes and diseases by sowing plants that release certain chemicals into the soil that inhibit the development of pests (secondary metabolites). These plants include, among others, some types and varieties of mustard. To achieve a positive effect, these biofumigant plants are usually crushed and incorporated into the soil.

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The biofumigation market was estimated to be worth USD 100 million in 2023, and is expected to reach USD 140.71 million by 2030, growing at a CAGR of 5% from 2024 to 2030. The agricultural industry focused on controlling soil pests and diseases with natural substances and procedures is known as the biofumigation market. The process of biofumigation involves the introduction of certain plants, mainly members of the Brassicaceae family (broccoli, radish and mustard), into the soil. These plants release glucosinolates when they are cut and added to the soil. Glucosinolates break down into biologically active chemicals, such as isothiocyanates, which are toxic to a variety of pests and soil-borne diseases. The growing popularity of this natural approach as a long-term replacement for chemical fumigants is in line with the growing need for environmentally responsible agricultural practices.

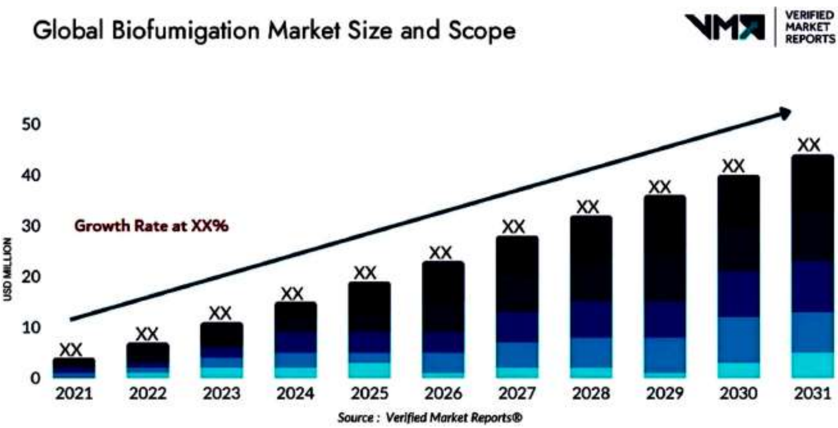

Figure 2.1 – Global biofumigation market by type (mustard seeds, cauliflower seeds), by application (fruits, vegetables), by geographic coverage and forecast. URL: https://www.verifiedmarketreports.com/download-sample/?rid=776826

The biofumigation market is fueled by several factors such as the growing trend towards organic farming and growing awareness about the harmful effects of synthetic chemical fumigants on the environment and human health. As part of Integrated Pest Management (IPM) practices, farmers and agribusinesses are increasingly using biofumigation to increase crop yields, improve soil health, and reduce dependence on chemicals. Moreover, biofumigation promotes biodiversity and reduces chemical residues in soil and crops and is in line with sustainable agriculture practices.

The biofumigation market can be segmented on the basis of crop type, end-user, and geographical region. Biofumigation methods are highly beneficial for crops such as ornamental plants, fruits, and vegetables. Research institutes, organic farmers, and commercial agricultural producers are some of the end users. Geographically, the market is spread across North America, Europe, Asia-Pacific, and other regions, with Europe driving adoption due to strict laws regulating chemical fumigants and active promotion of organic farming practices. The market is expected to expand as research and development in biofumigation continues to evolve, providing creative answers to the challenges associated with sustainable agriculture.

The biofumigation market is expanding significantly due to the growing interest in sustainable agricultural practices. Key changes include improved formulations of natural fumigators and increasing public awareness about the environmental benefits of biofumigation. In addition, changes in regulations supporting environmentally friendly pest management practices are fueling the market growth.Market research shows a growing preference for organic pest control methods among consumers and agricultural businesses. This is due to concerns about the health and environmental impact of synthetic fumigants. Biofumigants derived from natural materials such as essential oils and plant extracts offer a safer and sustainable alternative. This trend is expected to drive the biofumigation market, owing to increasing demand for organic food production and stringent regulations regarding synthetic fumigants.

Market research shows that advancements in biofumigation technology are increasing its efficiency and widening its application scope. New formulations, application methods, and combinations with other biocontrol methods are being developed to control a wider range of pests and improve efficacy. Research on biofumigants with specific target characteristics for different pests is also gaining momentum. These advancements are expected to make biofumigation a more competitive option in the overall pest control market.

Market studies show a shift towards regional production and distribution of biofumigants. This trend is driven by factors such as reducing transportation costs, minimizing environmental impact, and ensuring the quality and efficacy of biofumigants. Locally produced biofumigants can be customized to address specific regional pest problems and can provide greater freshness and efficacy than those transported long distances. This trend is expected to drive the regional biofumigation markets along with the established global players.

Leading companies in the biofumigation market:BASF SE, UPL Group, Isagro USA, Inc, Marrone Bio Innovations, Inc, Eastman Chemical Company, PH Petersen, Mighty Mustard, Tozer Seeds, Harley Seeds. Taking into account the data synthesis of Clarkson et al. (2020), who noted that many cruciferous species produce significant levels of glucosinolates (GSLs), which are held in plant cells separately from the enzyme myrosinase and are in themselves not fungitoxic (Manici et al., 1997).

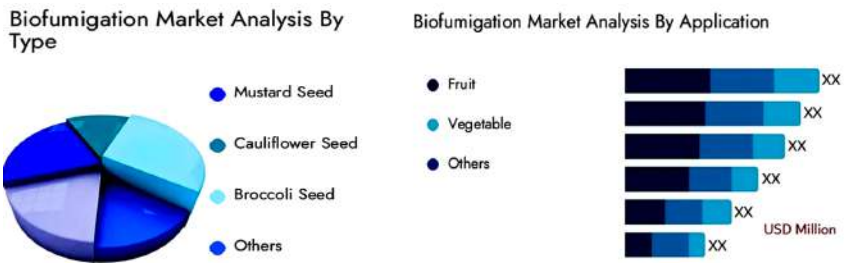

Figure 2.2 – Biofumigation market segmentation

The world experience of bofumigation is summarized in the review article by Kruger et al. (2013), the main points of which are presented below in the form of a literature review:

Principles of chemical soil fumigation (in accordance with the author's text of Kruger et al. (2013)). The primary aim of soil fumigation is to suppress soil-borne problems such as diseases, nematodes and weeds that might otherwise have a negative economic impact on the production of crops (Louvet, 1979). The first application of fumigation for the control of nematodes was recorded as early as in the 1870s (Van Berkum & Hoestra, 1979). In the years after the Second World War, several soil fumigants reached the market, including products such as chloropicrin, methyl bromide, 1,3-dichloropropene, ethylenedibromide, 1,2-dibromo-3-chloropropane and methyl isothiocyanate (ITC) (Lembright, 1990). However, for soil fumigation to be effective in the control of soil-borne pest and diseases, intensive research on the application rate and a sound knowledge of the soil and of the environmental conditions involved are required. It is also necessary to bear in mind the secondary, negative impacts of the use of this method on the soil (Louvet, 1979). Soil fumigation should be used as part of a holistic programme that follows a long-term approach (Louvet, 1979). Products such as methyl bromide, chloropicrin and combinations of chloropicrin and 1,3-dichloropropene must be applied by trained pest control operators to lower the risks involved when using fumigation products.

Fumigation of the soil is done before the planting or transplanting of seedlings to prevent a negative impact of the product on the crops planted. To increase the efficacy of soil fumigation, factors such as a knowledge of the crop involved, its correct seeding or planting date, the presence of soil-borne pests and diseases that might pose a problem to the specific crop, the availability of cultivars with resistance to certain soil-borne pest and diseases, and soil preparation should be taken into consideration before applying the product. Furthermore, knowledge of the pest or disease and its survival in the soil is also imperative for successful fumigation (Louvet, 1979).

Principles of soil biofumigation (in accordance with the author's text of Kruger et al. (2013)). Biofumigation takes place when certain soil-borne pests and diseases are suppressed as a result of the biocidal activity of glucosinolate-containing plants when they are incorporated into the soil (Kirkegaard et al, 1993, 1998). The fumigant action of the volatile compounds that are released during the biodegradation of organic matter suppresses plant pathogens (Piedra Buena et al, 2007).

Glucosinolates (GSLs) (glucose- and sulphur-containing organic anions) and ITCs are the main active compounds involved in biofumigation. The first observations of the unique properties of GSLs and ITCs were recorded at the beginning of the 17th century during efforts that were made to understand the reason for the sharp taste of mustard seeds (Challenger, 1959). GSLs are sulphur-containing secondary metabolites produced by certain crops that are hydrolysed by the enzyme myrosinase (MYR) to form ITCs, in a process that is known as the GL-MYR system (Wathelet et al, 2004). ITCs have a toxic effect on many soil-borne pathogens (Sarwar et al., 1998). Breakdown products, including the active compound

ITC, are released when the plant cell walls are damaged or broken during maceration of the plant biomass (Sarwar et al, 1998; Wathelet et al, 2004).

The role played by biofumigation in integrated pest management (IPM) (in accordance with the author's text of Kruger et al. (2013)). The positive biological activity of the GSL degradation products used for the suppression of some pathogenic fungi (Manici et al, 1997) and nematodes (Lazzeri et al, 1993) serves to open up new perspectives on IPM (Lazzeri et al, 2004), because it has been proven to be effective against weeds, plant diseases and nematodes (Van Dam et al., 2009). Numerous studies in the literature confirmed the ability of certain plants to suppress nematodes through the nematicidal activity of the secondary metabolites (Chitwood, 2002; Zasada & Ferris, 2004). Research has furthermore proved that many Brassica spp. show nematicidal activity on plant-parasitic nematode species such as M. incognita, M. javanica, Heterodera schachtii and Pratylenchus neglectus (Thierfelder & Friedt, 1995; Potter et al, 1998; Monfort et al., 2007).

Plants containing GSL (in accordance with the author's text of Kruger et al. (2013)). The Family Brassicacea (brassicas) contains more than 350 genera with 3 000 species, of which many are known to contain GSL. However, GSLs are not confined to brassicas alone. At least 500 species of non-brassica dicotyledonous angiosperms have also been reported to contain one or more of the over 120 known GSLs (Fahey et al., 2001). Each of the GSLs has its own chemical properties and can be placed in one of three different classes, namely aliphatic, aromatic or indole forms (Zasada & Ferris, 2004; Padilla et al, 2007). Most GSL-containing genera, however, are clustered within the Brassicaceae, Capparaceae and Caricaceae families (Rodman, 1981). The GSL concentration in the cells of the various plants in the families differs substantially. Therefore, it is crucial to identify species that will be effective in supressing soil-borne pests and diseases, including nematodes. Rotation crops tested for the presence of GSLs are provided in Table 1, which shows that it is mostly the brassicas that contain GSLs and that different levels of GSL exist within different genera (Larkin & Griffin, 2007). Therefore the plant species that generally are considered for biofumigation are found mostly in the family Brassicaceae, and include Brassica oleracea (broccoli, cabbage, cauliflower, kale), Brassica rapa (turnip), Raphanus sativus (radish), Brassica napus (canola, rapeseed) and various mustards, such as Sinapis alba (white mustard) and Brassica juncea (Indian mustard) (Sarwar et al., 1998; Ploeg, 2007).

Aspects that influence GSL release and ITC activity (in accordance with the author's text of Kruger et al. (2013)). Techniques that ensure the maximum rupturing/maceration of the cells involved, as well as effective incorporation, ensure the best release of ITC. This aspect, along with a variety that has a high GSL content and with enough water present for hydrolysis to take place, ensure optimum biofumigation (Brown *et al.,* 1991; Poulton & Moller, 1993; Morra & Kirkegaard, 2002; Matthiessen *et al.,* 2004). One way to ensure the effective release of ITC is to slash the leaves with a slasher and then to plough the slashed residues into the soil as soon as possible, using a rotavator or disc harrow (Fig. 2). A flail chopper ensures the best maceration results and, consequently, a good GL-MYS interaction for the release of ITC (D. Gies, personal communication). The latter technique remains applicable particularly for the *Brassica* spp. such as mustards, which have a high GSL concentration in the above-ground parts of the plant.

The growth stage of the crop (emergence, rosette, flowering, seed filling, ripening), the amount of biomass produced and the correct incorporation into the soil all contribute towards the success of biofumigation (Bellostas *et al.,* 2004) (Fig. 3). The flowering stage of the plant maintains a higher GSL content than the vegetative plant parts. The GL-MYS interaction can be expected to take place more effectively later in the growing season, prior to seed set. In the root tissue, the concentration of GSL is higher in the earlier root growth stage, with decreasing concentrations during the root growth cycle. Different types of GSLs are present in the roots and shoots of different plant species (Van Dam *et al,* 2009). Studies that were conducted by Van Dam *et al.* (2009), in which the root and shoot GSL of 29 plant species were evaluated for their GSL concentration and profiles, showed that the roots had a higher GSL concentration, as well as more diversity than the shoots. The root and shoot concentration of specific GSLs was found to differ from one another, with the most prominent indole GSL in the shoots being indol-3- yl GSL, and with the roots having higher concentrations of aromatic 2-phenylethyl GSL.

Low soil temperature slows down the enzymatic reaction during biofumigation, and therefore incorporation of green manure is not recommended at soil temperatures close to 0°C. The presence of organic matter seems to have an immobilising effect on the degradation products, thus preventing them from reaching the target pests (L. Lazzeri, personal communication).

The inclusion of sulphur fertilisers may improve the nutritional value of *Brassica* spp. Sulphur forms part of the process that takes place in the formation of secondary metabolites, *inter alia* GSLs. The level of GSLs is dependent on the genetic factors of the plant, but can also vary according to environmental conditions and the availability of soil sulphur (De Pascale *et* al., 2007).

Nematode host status of different biofumigation crops (in accordance with the author's text of Kruger et al. (2013)). The ideal cover crop to be applied in vineyards for nematode suppression should either be resistant or have a poor host status, in addition to having a biofumigation suppressing effect on the target nematode when applied to the soil as a green manure (Vianene & Abawi, 1998). The possibility exists that *Brassica* spp., if used as cover crops in vineyards, could also be susceptible to specific nematodes species that require suppressing. If the target pest manages to reproduce on the cover crop species before it is ploughed in as a green manure, these *Brassica* spp. cannot be recommended as a cover crop (McLeod & Warren, 1993).

Root-knot nematode species can complete their life cycle on several *Brassica* spp., but there are major differences in their susceptibility (McLeod & Steel, 1999). In a glasshouse study, Curto *et al.* (2005) evaluated the host status of different brassicas for *M. incognita.* Although all of the brassicas act as hosts, the life cycle of the nematode was in general much slower in comparison to tomato. These authors rated certain brassicas as poor or non-hosts (resistant), maintenance hosts (tolerant) or good host (susceptible). *Eruca sativa* cv. Nemat was evaluated for its potential as a trap crop for root-knot nematode. No eggs were produced in 80% of the plants, indicating that it has the potential to act as trap crop for *M. hapla* (Melakeberhan *et al.,* 2006).

However, when plant cells are ruptured the GSLs and myrosinase come into contact and are hydrolysed in the presence of water to release various products, including ITCs (Vig et al., 2009; Figure 2.3). ITCs have a wide range of biocidal characteristics and are acutely toxic to a variety of pests and pathogens (Chew, 1987). GSLs are в-thioglucoside N-hydroxysulfates, with a side group (R) and a sulphur-linked в-d-glucopyranose moiety (Fahey et al., 2001) and are classified as aliphatic, aromatic or indole GSLs according to the type of side chain (Fenwick et al., 1983; Figure 2.3). The R group is retained in the ITCs and influences its biological activity.

Biofumigation matter to the soil. This will increase soil aeration, water infiltration rates and soil water holding capacity. It also increases soil porosity if used as a green manure. It adds more organic carbon to the soil (Balesh et al., 2005) which is needed to increase the activity of soil fauna and flora. In particular, the activities of biological control agents like predaceous nematodes, protozoa, fungi and bacteria will be enhanced as the presence of organic carbon in the soil increases the saprophytic activities of microorganisms (Karavina and Mandumbu, 2012).

Biofumigation is the use of green manures crops which release biocidal molecules into the soil after their incorporation. This best practice was developed in several countries to cope with the withdrawal of methyl bromide, a most effective but controversial chemical soil fumigant. The effect of biofumigation is partly based on the release of natural toxic substances but also on their effect as a green manure plant.

For Brassicas, the transformation of glucosinolates into toxic and volatile isothiocyanates happens during the breakdown of the plant cells. The more cells which are broken and release glucosinolates, the higher the peak of isothiocyanates will be (Morra & Kirkegaard, 2002). This is critical for the efficacy of biofumigation. Therefore, the biofumigation crop should be shredded as finely as possible before soil incorporation (Figure 1), with the best method to use are mulching devices equipped with hammers rather than blades (Matthiessen et al., 2004).

The amount (concentration) of isothiocyanates needed for successful control depends on the targeted soilborne pathogens, nematodes and weed seeds (Klose et al., 2008). For the more resistant microsclerotia of the soilborne pathogen *Verticillium dahliae*, *Brassica* plants will not liberate sufficient isothiocyanates for a successful control in the field (Neubauer et al., 2014).

While biofumigation holds a lot of promise as a crop protection tool, its broad spectrum toxicity might harm non-target beneficial soil biota such as biocontrol agents or other pest antagonists (Ramirez *et* al., 2009). This means the switch to brassica biofumigants might not eliminate all the harmful non-target effects associated with synthetic chemicals, thus potentially complicating the integration of cultural and biological control. Henderson *et al.* (2009) reported that biofumigation interfered with the biological control of *Meloidogyne chitwoodi* by the entomopathogenic nematodes *Steinernema feltiae* and *Steinernema riobrave.* Biofumigants are also non-persistent. Thus, it does not provide a long term control option for pests. Farmers might have to complement biofumigation with other crop protection tools.

The nature of the soil is also an important factor when biofumigation is used as a control method. Lighter-textured soils with low organic matter content are better suited to this approach (Kirkegaard, 2009). Isothiocyanates get fixed to organic matter (sorption) and are therefore less active against soilborne pathogens and nematodes. Therefore, the lower the organic matter content, the less sorption of the isothiocyanates occurs in a soil. Lighter soils i.e., soils with a higher part of sand, allow a better diffusion of the toxic gases in the soil.

An alternative to increasing the amount of isothiocyanates in the soil is the use of defatted seedmeals from *Brassica* cultivars with high content of glucosinolates (Patalano, 2004). Such products are commercially available, and in most cases sold as organic fertilizers (Figure 2.2.1). Therefore, their efficacy is not known as such products do not undergo efficacy evaluation, as is the case when products are registered as pesticides. However, the amount of seedmeal added to the soil is limited by its nutrient content, usually nitrogen in the first instan ce. The addition of too much seedmeal can result in an over-fertilization and potentially in the leaching of different nutrient elements (such as nitrate).

Seedmeal products are mostly applied by broadcast in form of pellets or powder (Figure 2.2.2) and incorporated into the soil before the planting of the crop. Once in contact with water in the soil, the transformation of the glucosinolates into isothiocyanates takes place. Irrigation after the incorporation of these products accelerates this transformation and also favors the diffusion and dispersal of the isothiocyanates in the soil.

Figure 2.2.1 – Example of an organic fertilizer based on defatted mustard seedmeal (Michel and de Cara García, 2020)

Figure 2.2.2 – Pellets of defatted mustard seedmeal before incorporation in the soil (Michel and de Cara García, 2020)

Another way to apply isothiocyanates to the soil is the use of liquid *Brassica* seedmeal products. In this case, the seedmeal is manipulated before application. Through this manipulation, the glucosinolates are transformed into isothiocyanates and then dissolved in liquid which is applied to the soil through a drip irrigation system.

It is noted (Karavina and Mandumbu, 2012) that the most studies on biofumigation have been done with brassicas (Kirkegaard et al., 1993; Gouws, 2004; Kumar, 2005; Ramirez et al., 2009; Szczyglowska et al., 2011), but as already noted, other families contain plants with biofumigant properties. The decomposition of biofumigant plant tissues mainly releases isothiocyanates (ITCs), in addition to thiocyanates, nitriles and oxazolidinethiones (Kirkegaard and Sawar, 1998; Fahey et al., 2001). The ITCs are related to the active ingredients of metham sodium and dazomet. They are released following tissue damage, when endogenous myrosinase enzymes hydrolyze glucosinolates (GCs). GCs are sulphur-containing chemicals that are produced by plants as secondary metabolites (Agrios, 2005). They are found in the vacuole. In the plant, GCs are relatively inactive against microbes. But when hydrolyzed, the ITCs in particular, are biocidal to nematodes, bacteria, fungi, insects and germinating seeds (Sarwar et a/., 1998). There are over 120 ITCs (Fahey et al., 2001) that have been identified mainly from plants in the Brassicaceae family (van Dam et al., 2009) (Table 1).

The same studies (Karavina and Mandumbu, 2012) indicate that differences in structure of individual ITCs depend on their organic side-chain, which in turn, influence their biocidal activity (Rosa et al., 1997; Clark, 2010). The side chains may be aliphatic, aromatic or indole. Aromatic ITCs are mainly produced in roots and are very toxic (at least 50 times more toxic than metham sodium's methyl ITC) to a range of soil borne fungal pathogens (Vaughn et al., 1993). They have low volatility and long persistence in the soil.

This long persistence benefits crops grown after the GC-producing plants. Roots may release ITCs both during growth and decomposition. Aliphatic ITCs are more common in shoots. They are of higher volatility than root ITCs. Thus, shoots tend to have a lower concentration of ITCs than roots. Exposure of dry shoot residues to the surface after crop harvest, burning and grazing of residues reduce the amount of ITCs in shoots. The indole ITCs are found in both roots and shoots. In shoots, the predominant ITC is derived from the GC indol-3-ylmethylglucosinolate, while roots have 1-methoxyindol-3-ylmethylglucosinolate and 4-methoxyindol-3-ylmethylglucosinolate (van Dam et al., 2009).

The amount and profile of ITCs produced by brassicas vary with the species and with the soil conditions. Table 2 gives common sources of some ITCs. For example, the three major ITCs identified from Brassica juncea roots are 3-butenyl, 4-pentenyl and 2-phenyethyl, while from Brassica campestris and Brassica napus, the major ITCs are 3-butenyl, 4-pentenyl, 2-phenyethyl, 5-methylthiopentyl and benzyl.

Table 2.1

Plants with glucosinolates in their leaves and stems (Karavina and Mandumbu, 2012)

Plant Species	Common Name	Family
1	2	3
Alliaria petiolata	Garlic mustard	Brassicaceae
Arabidopsis thaliana	thale cress	Brassicaceae
Alima tetracantha	needle bush	Salvadoraceae
Brassica campestris rapa	turnip	Brassicaceae
Brassica carinata	Ethiopian mustard	Brassicaceae
Brassica fruticulosa	Mediterranean cabbage	Brassicaceae
Brassicajuncea	Indian mustard	Brassicaceae
Brassica napus	rape/canola	Brassicaceae
Brassica nigra	black mustard	Brassicaceae
Brassica oleraceae acephala	kale	Brassicaceae
Brassica oleraceae	cabbage	Brassicaceae
Cardamine cordifolia	Heartleaf bittercress	Brassicaceae
Cardamine diphylla	pepper root	Brassicaceae
Carica papaya	pawpaw	Caricaceae
Diplotaxis tenuifolia	Perennial wall-rocket	Brassicaceae
Eruca sativa	salad rocket	Brassicaceae
Lepidium sativa	garden cress	Brassicaceae
Moringa oleífera	Moringa	Moringaceae
Moringa stenopetala	cabbage tree	Moringaceae
Rhaphanus sativus	radish	Brassicaceae
Sinapis alba	white mustard	Brassicaceae
Thlaspi arvense	field pennycress	Brassicaceae
Tropaeolum majus	Indian cress	Tropaeolaceae
Alliaria petiolata	Garlic mustard	Brassicaceae
Arabidopsis thaliana	thale cress	Brassicaceae
A%ima tetracantha	needle bush	Salvadoraceae
Brassica campestris rapa	turnip	Brassicaceae
Brassica carinata	Ethiopian mustard	Brassicaceae
Brassica fruticulosa	Mediterranean cabbage	Brassicaceae

(End of Table 2.1)

1	2	3
Brassicajuncea	Indian mustard	Brassicaceae
Brassica napus	rape/canola	Brassicaceae
Brassica nigra	black mustard	Brassicaceae
Brassica oleraceae acephala	kale	Brassicaceae
Brassica oleraceae	cabbage	Brassicaceae
Cardamine cordifolia	Heartleaf bittercress	Brassicaceae
Cardamine diphylla	pepper root	Brassicaceae
Carica papaya	pawpaw	Caricaceae
Diplotaxis tenuifolia	Perennial wall-rocket	Brassicaceae
Eruca sativa	salad rocket	Brassicaceae
Lepidium sativa	garden cress	Brassicaceae
Moringa oleifera	Moringa	Moringaceae
Moringa stenopetala	cabbage tree	Moringaceae
Rhaphanus sativus	radish	Brassicaceae
Sinapis alba	white mustard	Brassicaceae
Thlaspi arvense	field pennycress	Brassicaceae
Tropaeolum maius	Indian cress	Tropaeolaceae

Table 2.1.1

Common sources of ITCs (Karavina and Mandumbu, 2012)

Isothiocyanates	**Common Sources**
Methyl	*Capparales,* metham sodium
2-Propenyl	B juncea, B carinata, B nigra
3-Butenyl	B napus, B campestris
4-Pentenyl	B napus, B campestris
Benzyl	*Sinapis* spp
2-Phenylethyl	*Brassica* roots

Table 2.1.2

Some commonly used biofumigant crops and their respective GSLs and ITCs (Clarkson et al., 2020)

Common name	**GSL**	**ITC**
Brown mustard *(Brassica juncea)*	Sinigrin	2-propenyl-ITC (= allyl-ITC)
Black mustard *(Brassica nigra)*	Sinigrin	2-propenyl-ITC (= allyl-ITC)
White mustard *(Sinapsis alba)*	Sinalbin	4-hydroxybenzyl-ITC
Radish *(Raphanus sativus)*	Glucoraphenin	4-methylsulfinyl-3-butenyl-ITC
Rocket *(Eruca sativa)*	Glucoerucin	4-methylthiobutyl-ITC

Table 2.1.3

Glucosinolates associated with brassica plants (Musa, 2021)

Glucosinolate	Common names	Brassica species	Plant organ	Author(s)
Aliphatic				
Gluconapin	Wild mustard	*Brassica rapa*	Shoot	Park *et al.* (2017)
Sinigrin	Indian mustard	*Brassica juncea*	Shoot	Zasada and Ferris (2004); Ngala *et al.* (2015)
	Ethiopian mustard	*Brassica carinata*	Shoot	Potter *et al.* (1998)
Sinalbin	White mustard	*Sinapis alba*	Shoot	Hopkins *et al.* (1998)
	White mustard	*Brassica hirta*	Shoot	Zasada and Ferris (2004)
Glucoerucin	Rocket	*Eruca sativa*	Shoot	Di Gioia *et al.* (2018)
Glucobrassi-canapin	Wild mustard	*Brassica rapa*	Shoot	Kim *et al.* (2010)
Progoitrin	Canola	*Brassica napus*	Seed	Cartea *et al.* (2008)
Glucoraphanin	Radish	*Raphanus sativus*	Shoot	Ngala *et al.* (2015)
	Rocket	*Eruca sativa*	Shoot	Di Gioia *et al.* (2018)
Aromatic				
Gluconasturtiin	Indian mustard	*Brassica juncea*	Root	Park *et al.* (2017)
	Radish	*Raphanus sativus*	Root	Ngala *et al.* (2015)
Glucotropaeolin	White mustard	*Sinapis alba*	Root	Sarwar *et al.* (1998)
	White mustard	*Brassica hirta*	Root	Zasada and Ferris (2004)
Glucosinalbin	White mustard	*Sinapis alba*	Seed	Borek and Morra (2005)
Indolyl				
Neoglucobrassicin	Canola	*Brassica napus*	Shoot	Potter *et al.* (1998)
4-methoxyglucobrassicin	Canola	*Brassica napus*	Shoot, Seed	Potter *et al.* (1998)

Commonly used biofumigant plants which include brown mustards, white mustards, radishes and rocket species contain different GSLs hence resulting in different ITCs being released (Table 2.1.2–2.1.3). Although some biofumigants have a dominant GSL (Table 1), others may contain a mixture. Different cultivars or plant parts may also contain different amounts or profiles of GSLs. For instance, 2 phenylethyl GSL is mainly produced in the roots of BB. napus(Potter et al., 2000).

Although ITCs have generally been the focus of biofumigation-related research and are considered the most bioactive of the hydrolysis products, other compounds such as non-glucosinolate sulphur-containing compounds, fatty acids, nitriles and ionic thiocyanates may also affect pest and pathogen populations (Matthiessen & Kirkegaard, 2006) and may explain why some low GSL brassica crops have been shown to have suppressive activity against soilborne diseases.

Clarkson et al. (2020) were noted that researchers have been trying to understand, demonstrate and optimise the biofumigation process, and as more studies have now employed quantification of GSLs or ITCs, it has become increasingly apparent that the beneficial effects observed may not always be related to the activity of GSL-based hydrolysis compounds and that other mechanisms may play a complimentary or more dominant role in disease suppression. This is probably as a result of incorporating large amounts of organic matter into the soil potentially resulting in improved soil structure, increased nutrient availability, increased water holding capacity and stimulation of beneficial/pathogen-suppressive microbial communities. However, disentangling the multitude of mechanisms which may operate is a challenge but advances in next generation sequencing to characterise microbial populations associated with the observed disease suppression may provide further insights for optimising ITC and non-ITC benefits of biofumigants.

Edwards & Ploeg (2014) noted that biofumigation is a rotation-based approach to crop protection in which *Brassica* cover crops in the family Brassicaceae (also called Cruciferae) are macerated and incorporated into soil prior to planting vegetables. During the leaf maceration process, sulphur-containing compounds known as glucosinolates combine with an enzyme called myrosinase to produce isothiocyanates and other chemical compounds. These broad-spectrum biocides are detrimental to weed seeds and a range of soilborne pests and pathogens, including nematodes. In this case, the flail mower on the rear tractor is mowing and macerating a Nemfix mustard (*Brassica juncea*) cover crop (shown in the background), while the rotary hoe is being used to immediately incorporate the leaves and shoots into the soil. The field was irrigated after cultivation to enhance the biofumigation effect, and cherry tomatoes were planted four weeks later.

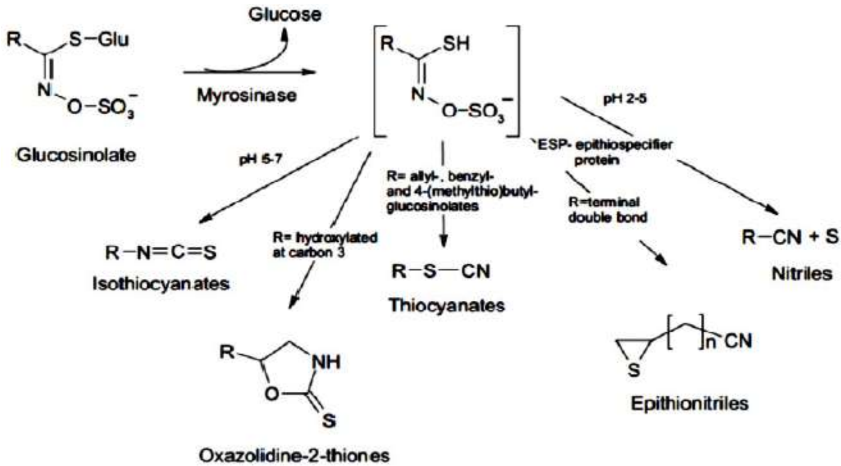

Figure 2.3.1 – Structure of possible glucosinolate degradation products (Musa, 2021)

The authors of the study (Edwards & Ploeg, 2014) also emphasize that although the term 'biofumigation' implies that the active ingredients are volatile, and act in much the same way as commercial fumigants, some of the most potent chemicals released from decomposing *Brassica* residues are not gaseous at ambient temperatures. Thus, it is important to recognise that these chemicals principally diffuse through soil in the water phase and do not act as true fumigants. Another point that must be recognised is that the term 'biofumigation' was initially used to describe the production of isothiocyanates from plant residues. However, the term is now commonly used when volatile substances are produced through microbial degradation of animal and plant organic amendments. Thus, plants such as neem, marigold and castor contain compounds that are toxic to nematodes and when they are used as soil amendments and nematode populations are reduced, it is considered a biofumigant effect. Similarly, when microbial fermentation of nutrient rich amendments such as velvet bean, sunn hemp and elephant grass produces toxins that are detrimental to nematodes, the term biofumigation is also used.

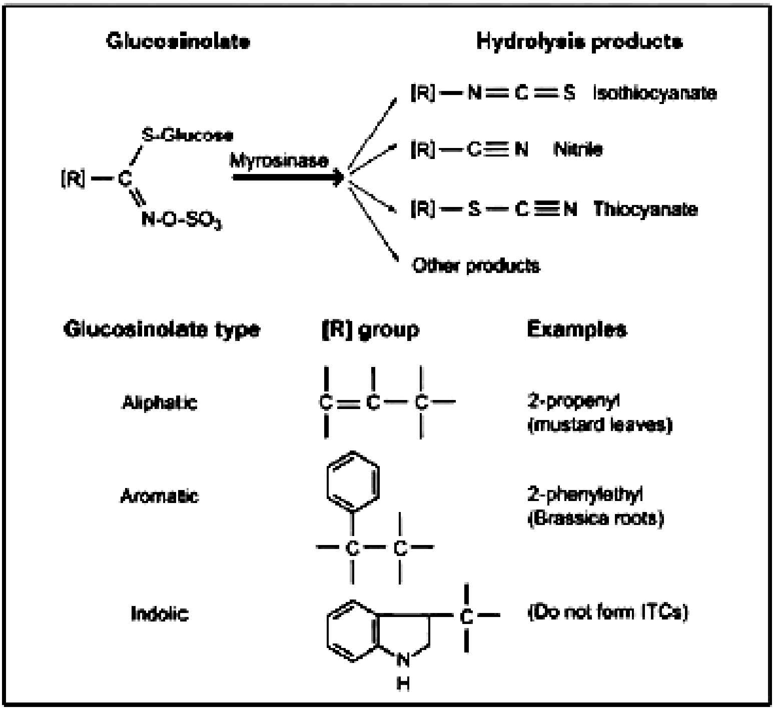

Figure 2.3.2 – Glucosinolate structure and products of hydrolysis (from Kirkegaard, 2009)

Based on the findings of these studies (Björkman & Shail, 2010; Edwards & Ploeg, 2014), the following generalizations were made:

– *Brassica* cultivars capable of producing large quantities of glucosinolates must be selected, and because sulphur is an important component of glucosinolates, the brassicas must be grown with optimal nutrition, particularly with regards to sulphur.

– Glucosinolate release from *Brassica* tissue must be maximised by incorporating the cover crop into wet soil at the time of maximum leaf area (i.e. before flowering). During the incorporation process, the leaf tissue must be macerated and disrupted as much as possible.

– To ensure that the volatile chemicals are retained within the soil profile, the field should be irrigated immediately with sprinklers to seal the soil surface, or the soil should be covered with plastic. As this is logistically difficult to do on a large scale, it is a major limitation of biofumigation.

When *Brassica* cultivars with high leaf glucosinolate concentrations are incorporated into soil as described above, nematicidal activity is not always high enough to control the nematode pest being targeted. For example, the damage threshold for root-knot nematode on crops such as carrot, tomato, potato, and sweetpotato is very low, and so biofumigation will often fail to reduce nematode populations to the required level. Also, research has shown that some nematodes (e.g. *Pratylenchus*) are less sensitive to brassicaceous seed meals than others.

Another major drawback of brassicas is that some species and cultivars are good hosts of root-knot nematode, the most important nematode pest of vegetables. Thus, *Brassica* cultivars need to be chosen carefully as there is a danger that the biofumigant crop will increase rather than decrease nematode populations. A paper by Edwards and Ploeg (2014) is worth consulting, as 31 plants in the family Brassicaceae were assessed in the greenhouse for their capacity to host three species of root-knot nematode (*Meloidogyne javanica*, *M. incognita* and *M. hapla*). Indian mustard (*Brassica j*uncea) and turnip (*B. rapa*) were generally good hosts of the two warm-climate species whereas most oil radish cultivars (*Raphanus. sativus* ssp. *oleiferus*) were poor hosts. Some oil radish cultivars were among the best hosts for *M. hapla*, while arugula (*Eruca sativa*) cv. Nemat was a poor host of all three nematode species.

In situations where cyst nematodes cause problems on vegetables, biofumigant crops also need to be chosen carefully because many cruciferous plants are good hosts of species such as *Heterodera schachtii* and *H. cruciferae.*

It is noted (Edwards & Ploeg, 2014) that there were many situations where brassicas will prove to be a useful rotation or cover crop. However, one question vegetable growers need to answer was whether they gain additional benefits from macerating the tissue and pulverising wet soils to achieve a biofumigation effect. This process not only destroys soil structure and is detrimental to soil health but also kills or disrupts the larger beneficial soil organisms, many of which are predators. *Brassica* cover crops provide the traditional benefits of a green manure (i.e. a break in the vegetable rotation and inputs of organic matter), but the additional costs of macerating the biomass and incorporating it into soil may not be justified due to the negative effects on soil health.

The benefits obtained from using brassicas as a green manure rather than a biofumigant crop can be determined by establishing strip trials in which the *Brassica* biomass is incorporated aggressively into the soil in some parts of the field and treated as a cover crop in other areas. The costs of the incorporation process, together with data on disease incidence and severity in the following vegetable crop, will indicate whether it is economically worthwhile spending additional time and money trying to achieve a biofumigation effect.

In their publications, Duff et al. (2020) note that biofumigation is the practice of growing specialised cover crops for suppression of soilborne pathogens, pests and weeds. The cover crop produces naturally occurring compounds that are toxic to many soilborne pathogens that impact on Australian vegetable crops. Some soilborne diseases can survive for many years, even in the absence of a suitable host. The resting stages of some soilborne pathogens, can remain dormant until conditions are favourable, resulting in the development of symptoms on the plant. For some diseases like white rot (*Sclerotium cepivorum*) in onion, the pathogen can survive in the soil for 20 years or more.

It also indicates (Duff et al., 2020), що the challenge from a disease management perspective is reducing disease inoculum in the soil, whilst maintaining or enriching soil health so that crops are able to become more resilient to soilborne pathogens. An integrated approach utilising biofumigant cover crops can be an effective tool in the management of soilborne diseases in horticultural production systems. This offers growers a solution that does not involve the use of synthetic pest control. Brassica species, such as mustard, radish and rocket, have been shown to suppress soilborne diseases such as basal rot (*Sclerotium rolfsii*), Onion white rot (*Sclerotium cepivorum*), charcoal rot (*Macrophomina phaseolina*) and white mould (*Sclerotinia sclerotiorum*) (Figure 2.4). They achieve this through processes resulting in the release of naturally occurring chemicals contained in plant tissue.

Brassicas naturally produce a group of chemicals known as glucosinolates (GSLs). The highest concentration of glucosinolates tends to occur at approximately 25% flowering, which is the recommended timing for incorporating biofumigants. Through the process of mulching and incorporation, glucosinolates are released from the plant cells. Once released from plant cells and with the addition of irrigation water, glucosinolates are converted by the enzyme myrosinase into isothiocyanates (ITCs), gases that are toxic to various soilborne pathogens and pests. Irrigation and/or rolling helps to seal the gas in the soil so that they are most effective in suppressing pathogens (Duff et al., 2020).

There are over 137 glucosinolate compounds commonly found in brassica plants. The concentration and type of GSLs will vary between varieties, as does the type of ITCs produced from the GSLs. The ITCs determine the biofumigants' toxicity to various soilborne pathogens and pests. All biofumigant varieties have positive soil health benefits, but some may be better suited for a particular cropping program. This will depend on the soilborne disease being targeted as well as other considerations such as cropping window and agronomic management of the biofumigant (Figure 2.4) (Duff et al., 2020).

The soilborne disease that requires management, and time of year available to plant a cover crop, will impact which variety is most suitable. The matrix (Table 2.1) is a tool designed to assist decision making about variety selection for disease management. The table is based on key production breaks when a biofumigant cover crop is most likely to be included as part of a cropping system and the relative efficacy of biofumigant varieties against a range of soilborne diseases.

The authors of the study (Duff et al., 2020) also suggest the days to incorporation varied between different varieties and growing seasons. Generally, biofumigants reached incorporation (or 25% flowering) faster and produced less biomass in summer compared to winter (Figure 2.6).

Varieties	Season	Biofum	Black Jack Radish	BQ Mulch	Caliente	Cappucchino	Fallow	Fungisol	Mustclean	Nemat	Nemclear	Nemcon	Nemfix	Nemsol	Terranova Radish	Tillage Radish
Sclerotium rolfsii (basal rot)	Summer	•	••	•	••	•	••	•	•••	•	•	•	•	ND	ND	•
	Autumn	•	ND	•	••	ND	•	ND	•	ND	•	•	•	ND	ND	•••
	Winter/Spring	•	••	•	•••	•	•	•	•••	•	ND	ND	••••	••	••	•
Sclerotinia sclerotiorum (white mould)	Summer	••••	••	••••	•••	••	••••	•••	•••	••••	•	••	••••	ND	ND	••••
	Autumn	•	ND	•	•	ND	•	ND	•	ND	•	•	•	ND	ND	•
	Winter/Spring	••	•	••	•	•	•	•••	•	••	ND	ND	•	••	••	••
Macrophomina phaseolina (charcoal rot)	Summer	•••	••	•••	••••	•	•••	•	••••	•••	•	••	•••	ND	ND	•••
	Autumn	•	ND	••	••	ND	••	ND	•	ND	•	•	•	ND	ND	•
	Winter/Spring	•••	••	•••	•••	••••	••	••••	•••	••••	ND	ND	•••	••	•••	••••

Percentage mortality pink 0–20; orange 2–40; yellow 41–60; green 61–80; white 81–100.

Figure 2.4 – Suppress soilborne diseases due to biofumigation with cruciferous crops (Duff et al., 2020)

As brassicas are predominantly a winter-grown crop, biomass production is greater in the cooler months, compared to summer. However, having high biomass does not mean that these varieties will produce more GSLs.

Glucosinolates or GSLs are the precursors to the toxic compounds, isothiocyanates or ITCs, that have suppressive activity against soilborne pathogens. As the ITCs are volatile gases, GSLs within the plant are measured instead as they are less volatile. Biofumigant varieties can have a range of individual glucosinolates, with varying concentrations.

While some GSLs are known to be more toxic in the ITC they are converted to, glucosinolate data in this guide is presented as total glucosinolate concentration rather than individual GSLs. However, higher total GSLs does not necessarily equate to greater activity against soilborne diseases.

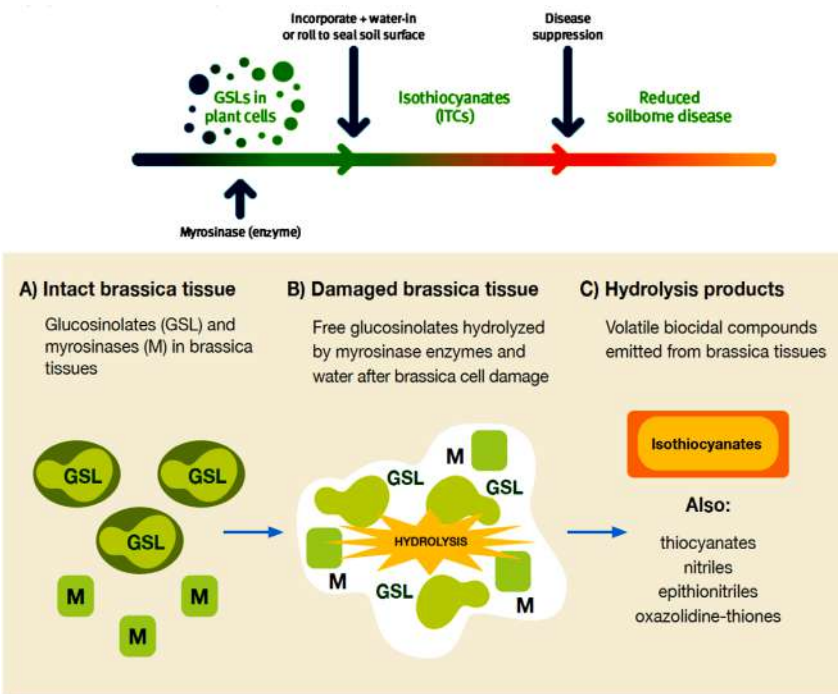

Figure 2.5 – The biofumigation process in brassica plants (Duff et al., 2020)

Brassica biofumigant cover crops are prone to a similar pest spectrum as commercially grown brassica crops, such as broccoli and cabbage. Generally speaking, biofumigant cover crops will not require the intensive pest management of commercial crops for various reasons:

The authors of the study (Duff et al., 2020) also draw conclusions:

– There is greater flexibility in thresholds and acceptable damage limits in crops not destined for human consumption.

– There are some benefits to the crop’s performance as a biofumigant if it is allowed to experience a moderate level of stress, whether this is insect feeding or some other stress (such as water stress) – this results in some increase in potency in GSLs, but this is variety dependant.

– The biofumigant cover crop can also provide functions beyond its soilborne disease suppression properties. For example, they can act as a nursery for beneficial insects, which would colonise vegetable crops and attack the relevant pests.

– Management of insect pests in biofumigant crops is generally not required, and may be considered economically unfeasible. However, you should still monitor biofumigant crops if you wish to get the most benefit from growing them. Biofumigants are highly attractive to all beneficial insects particularly if flowers are present as many beneficial species are nectar feeders (e.g. parasitoids and hoverflies).

– Biofumigants have high requirements for nitrogen and potassium as well as sulphur, as the glucosinolates are sulphur containing compounds. Nutrient requirements for summer grown biofumigants were roughly half of that when grown in winter. This reflects the difference in biomass between growing seasons. Tillage radish was the exception with similar biomass and nutrient requirements whether grown in summer or winter. As biofumigants are fully mulched and incorporated, any applied nutrients will be available through nutrient recycling for future crops.

– Research looking at the effect of drought stress on GSLs and biofumigant efficacy has shown that moderate to high water stress increases the concentration of GSLs per kg of plant tissue, even though the amount of biomass is less. Comparison of biofumigants grown under high, medium and low irrigation frequencies showed biomass was reduced by 45–55% between high and low irrigation treatments for 3 out of the 4 varieties in summer. The impact of irrigation strategy on biomass was not as significant for winter grown biofumigants with at most a 24% lower biomass in Nemat with low irrigation frequency.

– Irrigation treatment. Winter growing season The low irrigation treatment was established and then grown on rainfall only receiving 0.7–0.75 ML/ha, medium irrigation received 1.57–2.27 ML/ha and the high irrigation received 2.07–3.17 ML/ha depending on harvest date. Summer growing season: The low irrigation treatment was established and then grown on rainfall only receiving 1.4–2.5 ML/ha, medium irrigation received 2.5–3.2 ML/ha and the high irrigation received 3.3–6.I ML/ha depending on harvest date.

– Biofumigants do not have to produce high levels of biomass to be effective in suppressing plant pathogens. Results from the irrigation trial showed that low irrigation produced a lower biomass crop yet the highest production of GSLs per hectare in 3 out of the 4 varieties with a winter planting. A summer planting was the reverse with 3 out of the 4 varieties producing more GSLs with the higher irrigation. While total GSLs have been measured, these values are only indicative and do not reflect the toxicity of the resulting ITCs on plant pathogens.

– Weed management for Biofumigants: it is recommended that weeds are managed as per a commercial crop. Pre-emergent herbicides like Dacthal® 900 WG (Nufarm) (active ingredient: Chlorthal-dimethyl) is registered for use in mustard crops as is Dual Gold (active ingredient: s-metolachlor). Care needs to be taken when using herbicides as most will have plant back issues for following cash crops. Biofumigant crops that are left to go to seed can be a weed in their own right. To avoid this, incorporate plant material at 25% flowering stage to maximise the disease suppression properties of the crop and to avoid plants going to seed and becoming weeds themselves. Before using any herbicide always read and comply with label requirements.

– Rotary hoe has been the recommended incorporation method for biofumigant cover crops. However, as not all vegetable growers have access to a rotary hoe, DAF also looked at a range of incorporation methods for biofumigant cover crops. These include: Mulching followed by Disc Plough or Rotary Hoe, then Irrigation or Rolling, and Strip till followed by irrigation. Strip tillage showed the most variability in biofumigant activity. Mulch/rotary hoe/irrigation and mulch/disc plough/irrigation were similar in their biofumigant activity. There was also little difference between irrigation and rolling post incorporation (Figure 2.7–2.8, Table 2.3–2.4).

Spraying off the biofumigant cover crop was also evaluated to see if it still retained its suppressive characteristics once incorporated post spraying. The crop was sprayed off at 25% flowering and incorporated 4 weeks later. Total GSL levels were measured 2 weeks post spraying and 4 weeks post spraying (incorporation). Comparison of GSL data showed a progressive decline in total GSL levels by 50% at 2 weeks post spraying and by 90% at 4 weeks, incorporation.

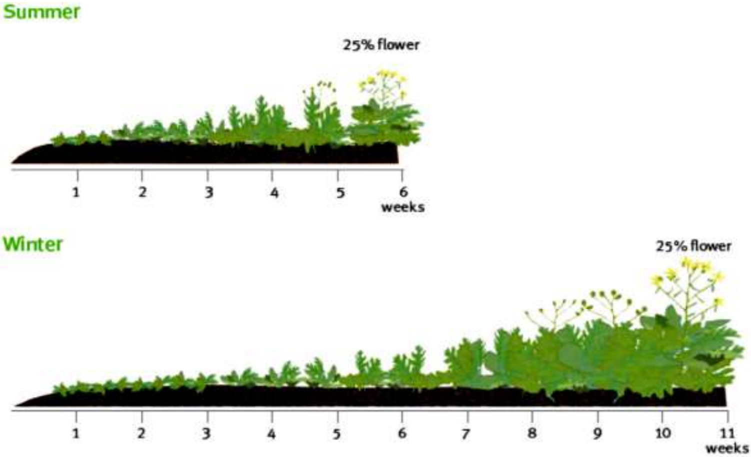

Figure 2.6 – Graphic depicting biofumigant cover crop days to incorporation across different growing seasons (Duff et al., 2020)

Figure 2.7 – Biofumigant varieties: Caliente (left), Nemat (right) and Oilseed Radish (bottom)

Table 2.2

Common commercially available biofumigant varieties compared in DAF trials (Duff et al., 2020)

Trade name	Variety	Species name
Biofum™	Doublet oilseed radish and Achilles white mustard mix	*Raphanus sativus* and *Sinapis alba mix*
Black Jack Radish™	Oil Radish	*Raphanus sativus*
Black Mustard	Black mustard	*Brassica nigra*
BQ Mulch®	Black mustard and Ethiopian mustard	*Brassica nigra* and *Brassica carinata*
Caliente™ including Caliente Rojo™	Indian mustard	*Brassica juncea*
Cappucchino™	Ethiopian mustard	*Brassica carinata*
FungiSol™	Ethiopian mustard and Terranova oilseed radish mix	*Brassica carinata* and *Raphanus sativus*
Mustclean™	Indian mustard	*Brassica juncea*
Nemat™	Rocket	*Eruca sativa*
Nemfix™	Indian mustard	*Brassica juncea*
Nemclear™	Fodder mustard	*Brassica napus*
Nemcon™	Fodder mustard	*Brassica napus*
NemSol™	Terranova oilseed radish and Nemat mix	*Raphanus sativus* and *Eruca sativa*
Terranova Radish™	Oilseed radish	*Raphanus sativus*
Tillage Radish®	Oilseed radish	*Raphanus sativus*
White Mustard	White mustard	Sinapis alba

Biofumigant activity against known pathogens varied greatly with the spray-off/incorporation methods. While some of these results reflect the significant decline in total GSL with time after spraying off, others do not. Further work on this as an option for biofumigant cover crop management is required.

Apply nitrogen at rates of 100–150 kg/ha and sulphate at 25-50 kg/ha. Biofumigant crops should also be succulent at early to mid-flowering to aid maceration implements in cutting and pulping biofumigant material. Nitrogen helps to produce a lush canopy which breaks down easily. Irrigation can also help to prevent early senescence.

Figure 2.8 – Steps involved in mulching and incorporation of biofumigant cover crops (in accordance with Duff et al., 2020)

Table 2.3

Efficacy matrix showing the extent of pathogen mortality after different methods of incorporation (in accordance with Duff et al., 2020).

Pathogen	Fallow (Field control)	Mulch + Disc plough + Irrigation	Mulch + Disc plough + Roll	Mulch + Rotary hoe + Irrigation	Mulch + Rotary hoe + Roll	Mulch + Strip till implement + Irrigation
Sclerotium rolfsii (basal rot)			••••			
Sclerotinia sclerotiorum (white mould)	••••	•••	••••	••••	••••	•••
Rhizoctonia sp. (wire stem)			•••	••••		••••
Macrophomina phaseolina (charcoal rot)	••••	••••	•••	•••	••	••
Verticillium dahliea (verticillium wilt)		••••	••••			••••
Sclerotium cepivorum (onion white rot)	••••	••••	••••	••••	••••	•••

Percentage mortality pink 0–20; orange 2–40; yellow 41–60; green 61–80; white 81–100.

Leafy biofumigants such as Indian mustard and rocket are more easily macerated and so release isothiocyanates more readily. Large root crops, such as oil radish, do not break down easily. However, brassica roots release glucosinolates into soil during growth in what is known as partial biofumigation. Many brassica species, including Indian mustard, oilseed radish and rocket, have been shown to suppress PCN during the growing period.

*Biofumigant maceration and incorporation techniques***.** Many options are available for biofumigant maceration and incorporation. Maceration techniques should pulp, twist or tear biofumigant material rather than just cut. This is to cause widespread rather than localised tissue damage.

Isothiocyanates disappear within minutes, so incorporate immediately after maceration. The time gap should be no more than 20–30 seconds. Mix biofumigant material evenly into soil, to a depth of 25–35 cm. If the crop has high biomass, incorporate to 35 cm. Some spaders can incorporate to 40 cm. Then seal the soil to retain toxic gases. A rotavator hood or spader smear roll can create an effective soil surface seal. The best systems use a front-mounted haulm topper, followed by a rear-mounted rotavator or spader, (Figure 2.8.1). If a rotavator has a shallow working depth, follow it with a plough to mix the material to a greater depth. Then use a plough-press, power-harrow with packer roll, or other rolls to reseal the surface (Figure 2.8.2). Minimise the number of passes because each extra operation moves soil and allows escape of toxic isothiocyanate gas. Figure 4 shows a single-pass system.

Table 2.4

Efficacy matrix showing the extent of pathogen mortality with different incorporation methods (in accordance with Duff et al., 2020).

Pathogen	Fallow (Field control)*	Spray-off + Disc plough + Irrigation	Spray-off + Disc plough + Roll	Spray-off + Rotary hoe + Irrigation	Spray-off + Rotary hoe + Roll
Sclerotium rolfsii (basal rot)					
Sclerotinia sclerotiorum (white mould)	••••	...	...		
Rhizoctonia sp. (wire stem)	••••	••			
Macrophomina phaseolina (charcoal rot)	...				
Verticillium dahliea (verticillium wilt)					
Sclerotium cepivorum (onion white rot)	••••	...			

Percentage mortality pink 0–20; orange 2–40; yellow 41–60; green 61–80; white 81–100.

*Fallow samples were taken at incorporation, 4 weeks after the biofumigant was sprayed.

Figure 2.8.1 – Single-pass biofumigation system: A = tine arrangement on a haulm topper, B = rotavator with rigid tines and S-blades, C = a single-pass system using front-mounted haulm topper and rear-mounted rotavator, and D = good-quality brassica residues following maceration (AHDB PCN, 2020)

Figure 2.8.2 – Multiple-pass biofumigation system: tractor A flail topping and shallow rotavating, followed by tractor B ploughing to 30 cm, followed by tractor C power-harrowing with packer-roll. The two implements on tractor A achieve full maceration and partial incorporation, allowing a short gap before tractor B fully incorporates and tractor C seals (AHDB PCN, 2020)

Soil moisture at incorporation affects biofumigation success. In sandy loam soils, aim for 25–75% of field capacity. Soil at this moisture range feels damp and will hold its shape when moulded or pressed. Isothiocyanate gases escape too easily from drier soils and cannot spread as effectively through wet soils. Incorporate lower biomass crops in soil at 25–50% of field capacity. Incorporate higher biomass crops at 75% soil moisture.

In his research, Caldbeck (2022) notes:

– crop type-to maximise on glucosinolate, the choice of crop species and cultivar is important. Plants have been found to be the most consistent in causing reductions in pests and pathogens. Oilseed radish had a big potential. White mustard should not be considered because it does not produce the right type of glucosinolates. It is important to maximise the volume of material produced from the brassica plants (which need adequate water and nutrition). Aim at producing 50 tonnes of fresh weight, up to 10 tonnes of dry weight per hectare. In contrast to standard cover cropping, you are trying to maximise biomass and glucosinolate content (quantity and quality). Nitrogen (N) is important for biomass and sulphur (S) for glucosinolate content. Aim at 100 kg per hectare (ha) of N and 25 kg per ha of S. For organic systems, aim at utilising nutrients from previous crops such as peas or legumes to feed the biofumatory green manure (mustards can be very good at mopping up and recircu-lating surface nutrients). If incorporating a 2-year break crop into your rotation (i.e. with legumes or clover), consider reducing it to 18 months and utilising the nutrition to feed the biofumatory crop.

– sowing date should be as early as possible (in an arable rotation, sowing in June – July has been found to produce the highest biomass and highest glucosinolate content – due to higher UV, temperatures and longer day length). Plant seeds into clean moist ground, so they can race ahead of and suppress weeds.

– damaging the plant cells allows the glucosinolates and myrosinase to interact with one another – this can be done by flailing, cutting and bruising the tissue as much as possible. Early flowering is when there is a peak of glucosinolates in the plants so this is the best time to cut (this would typically be within 10–16 weeks into growing time). Flowers may be at different stages – cut when the majority are closest to early flower as possible (once seed pods are formed it is too late). Outside, applying a light roll over can be beneficial. This should ideally be done coming up to early flowering.

– the volatile organic compounds are lost quickly (within the first 5 hours) after chopping and incorporating the plant material, therefore it needs to be buried quickly. Ideally, incorporate straight after chopping. It is recom-mended to use a front mounted flail followed by a rear mounted rotavator, and to compress in a one pass system if possible. If growing in protected cropping, it is possible to strim plant material into small pieces, then rotavate it in. Do this a bit at a time, and then apply water. A mower could alternatively be used – pull the whole plant up, roll over it lightly with the mower, then work it in.

– when about to incorporate the plant biomass, make sure the soil is moist enough. It may be best to wait for rain before incorporating (but avoid soaking wet soil). The aim is to enable the release of as much of the volatile gases in the soil as quickly as possible. 75% field capacity is best for optimising the hydrolysis and the biofumigation. The soil temperature needs to be above 8 ^{0}C for optimal movement of the volatile compounds.

– watering-In protected cropping, consider covering (i.e. with polythene) to lock in the volatile gases and leaving it on for a few days to a week (most of the biofumigation happens in the first 24–48 hours). Make sure the soil moisture is good beforehand, watering on top also creates a bit of a cap. On a field scale, irrigate after incorpo-rating – the equivalent of about half an inch. This will create the chemistry and seal it in.).

– Crop management-It is important to leave a gap between incorporating the biofumigant crop and planting a cash crop, in order to allow sufficient time to ventilate the soil. Allow a 2-week margin to be safe (even though isothiocyanates are lost within the first 5 hours, there are other volatile compounds that come later). Growing successive crops may lead to a greater suppression of certain soilborne pests and pathogens e.g. potato cyst nematodes.

According to a number of estimates (International Biofumigation Network, 2020; AHDB PCN, 2020; AHDB Biofumigation Report, 2022) biofumigant seed usually costs £5–9/kg. Seed costs are £60–100/ha for Indian mustard, rocket and oil radish. Establishment costs £15–30/ha. For spring and summer systems, fertiliser improves efficacy. Nitrogen at 100–150 kg/ha costs £80–160/ha, and sulphate at 25 kg/ha costs around

£25–50/ha. One 25 mm irrigation event would cost £85–155/ha. Machinery running costs are usually £100–150/ha. Total cost for a low-input overwintered system is about £270/ha for an expected efficacy of, at most, 10–30%. A spring or summer system is more likely to cost in the region of £400–450/ha but could extend to £675/ha. A maximum of 40–70% efficacy should be expected. Biofumigants also provide benefits from adding organic matter to the soil. A drawback of biofumigation is that it requires more time and attention from the grower than the use of synthetic nematicides.

Table 2.4.1

Summary of biofumigation recomendations for spring and summer windows (AHDB PCN, 2020)

Description of operation or crop management input	Comments
1	2
Biofumigant selection	Select a high-sinigrin-content Indian mustard biofumigant, and/or a rocket variety high in gluconasturtiin or glucotropaeolin glucosinolates
Preparation of soil and drilling	Drill biofumigants, between mid-July and mid-August, to a depth of 2-3 cm
Seed rate	Use a 8-10 kg/ha seed rate
Nutrient inputs	Apply nitrogen at 100-150 kg/ha, and sulphate at 25-50 kg/ha
Herbicides	Generally not required. If weed burden is high, seek advice from a qualified agronomist
Irrigation	May be required for establishment, to prevent early senescence or ahead of incorporation if soils are below 50% of field capacity (target 25-75% of field capacity)
Timing of maceration and incorporation	Macerate at early to mid-flowering when brassica foliage is still succulent. The best crops should be 50 t/ha of fresh biomass or greater, probably at 1.2-2.0 m in height
Foliage maceration	Use a flail or haulm topper for maceration, fitted with blunt hammer or solid V-tines. Front-mount maceration implements where possible. Keep tractor forward speed as slow as practicable to reduce the bite length of the macerator. The aim is to produce biofumigant pulp
Incorporation of residues	Ideally, rear-mount a rotavator or spader. Other incorporation implements can be used, provided material is well mixed into the top 30 cm of soil and incorporated within 20-30 seconds of maceration. Seal the soil either by smear-roll, heavy flat roll, or by the hood of a rotavator

(End of Table 2.4.1)

1	2
Planting the next crop in the rotation	Leave at least 2 weeks between incorporating a biofumigant and planting a new crop. This is to avoid phytotoxic effects in the new crop from biofumigant organic matter breakdown
Summary of biofumigation recomendations for winter windows	
Biofumigant selection	Select an oil radish rich in the glucosinolates gluconasturtiin or glucotropaeolin. Some Ethiopian mustards *(Brassica carinata)* may also be suitable. They are similar to Indian mustard, but hardier
Preparation of soil and drilling	Drill biofumigants to a depth of 2-3 cm between early and mid-September for best establishment
Seed rate	Use a 15-20 kg/ha seed rate (10 kg/ha-for Ethiopian mustard)
Nutrient inputs	Apply nitrogen at 30-40 kg/ha, and sulphate at 15-20 kg/ha
Herbicides	Generally not required. If weed burden is high, seek advice from a qualified agronomist
Irrigation	Typically not required
Timing of maceration and incorporation	Macerate ahead of planting a spring crop. Leave the biofumigant as long as possible to capitalise on partial biofumigation
Foliage maceration	Use best practice where possible. Efficacy is less than in summer and spring systems
Incorporation of residues	Use best practice where possible. Ensure residues are incorporated to at least 25 cm depth. Efficacy is less than in summer and spring systems
Planting the next crop in the rotation	Leave a minimum of 2 weeks between incorporating an overwintered biofumigant and planting a new crop. This is to avoid phytotoxic effects in the new crop from biofumigant organic matter breakdown

Biofumigation success is also subject to environmental conditions, more so than with granular nematicides. The combination of both management systems is advised for long-term PCN management.

Biofumigants are susceptible to pest damage and disease, the same as any cash crop. Crops can recover from pigeon feeding, but it delays biomass production, enables weeds to compete and causes early senescence. Biofumigant crops can increase the risk of introducing clubroot to oilseed rape or vegetable brassicas. Request information from seed suppliers on varietal resistance to clubroot. Some oilseed radish varieties are resistant, but most mustards and rocket are not.

The biofumigation efficiency of cover crops has been studied in terms of their glucosinolate content. Thus, Hansen (2011) noted that all forms of fumigation, biofumigation can impact living organisms in the soil, such as beneficial microbes including earthworms. Biofumigant activity against beneficial microorganisms such as *Trichoderma* spp. and *Bacillus amyloliquefaciens* was assessed in the laboratory. The biofumigants tested were found to be more suppressive against *Trichoderma spp.* than *Bacillus amyloliquefaciens.* There was variability in the suppression of beneficial microorganisms between varieties with some varieties suppressing more than others. Caliente in particular, showed high levels of suppression of *Trichoderma* spp. There was a trend for greater activity against beneficial microorganisms from biofumigant material grown during summer, however, this was not always the case. Therefore, if using biocontrol products such as *Trichoderma* spp. or *Bacillus* spp., it is recommended to only use these products when planting your cash crop and not in conjunction with the biofumigation crop.

The suppression of soilborne pathogens has also been linked to factors other than biofumigation. These include competition by a range of copiotrophic soil microorganisms, which thrive under the addition of fresh organic matter, proliferation of *Streptomycetes* (filamentous bacteria that have a role in breaking down plant material), and elevated soil populations of ammonia-oxidising bacteria, or the formation of additional bioactive sulphur containing compounds.

Biofumigation activity is known to increase soil bacterial diversity, but also significantly reduces soil fungal diversity, possibly due to reduced pathogenic fungi. This will obviously depend on the biofumigant variety, as different varieties contain varying types of GSLs with varying levels of toxicity when converted into ITCs.

Brassica biofumigant cover cropping is an option for vegetable system rotations as part of an integrated disease management strategy. Key information from this guide highlights several key considerations for those wanting to incorporate brassica biofumigants into their rotation.

Back et al. (2019) studied the glucosinolate profile of a number of cruciferous crops from the point of view of their use as a biofumigant (Figure 2.9).

A full-fledged assessment of the glucosinolate structure of cruciferous crops was carried out in the studies of Kirkegaard & Sarwar (1998) (Table 2.5).

Aliphatic GSLs dominated the shoot profiles of all Brassica species while some weed species contained higher concentrations of aromatic

GSLs (Tables 2.6–2.7). Indolyl GSLs were ubiquitous, but present in relatively low concentrations (<1 ^mol g-1) except in some of the *B. oleracea* vegetables. The concentration of major individual GSLs generally varied from two to ten fold within species (Table 2.5) as did total glucosi-nolates (Table 2.6). These differences were significant based on the LSDs calculated for individual or total GSLs in the representative entry selection (Tables 2.5 and 2.6). *B. napus* and *B. campestris* entries had similar shoot GSL profiles dominated by 3-butenyl GSL, 4-pentenyl GSL and their hydroxy-substituted forms, and also contained significant levels of the aromatic 2-phenylethyl GSL.

		Glucosinolate content (μmol g^{-1} dry weight)					
Species	**Cultivar**	**Glucoraphanin**	**Sinigrin**	**Sinalbin**	**Glucotropaeolin**	**Glucobrascicin**	**Gluconasturtiin**
B. caratina	Cappuccino		11.70			0.20	
B. juncea	ISCI 99		26.73			0.32	
B. juncea	Pacific Gold		25.95				
B. juncea	Scala		7.57			0.09	
B. juncea	Vitasso		20.79			0.50	
B. juncea	Keva			46.76	0.72	0.24	
S. alba	Ida Gold			31.20	0.48	0.13	
S. alba	Smash			32.65	1.54	0.04	
S. alba	Loti			12.25	0.22	0.07	
E. sativa	Trio	19.18		0.04			0.16
E. sativa	Nemat	6.62				2.59	
R. sativus	Bento					0.20	
R. sativus	Doublet					1.24	0.21
R. sativus	Anaconda					0.60	0.11
R. sativus	Terranova					3.24	0.28

Figure 2.9 – Glucosinolate profile of the biofumigant lines used in the poly-tunnel experiment at Harper Adams University (Back et al., 2019).

The authors of the study (Kirkegaard & Sarwar, 1998) note that maximum concentrations of these glucosinolates were two to ten times higher in B. napus oleifera biennus than *B. napus* oleifera annua while *B. napus* rapifera was intermediate.The B. oleracea vegetables had lower concentrations of the three alkenyl aliphatic GSL dominant in other species, but higher concentrations of the methylthio and methylsulphinyl analogues as well as significant concentrations of the indolyl GSLs particularly 3-indolyl-methyl GSL and 1-methoxy-3-indolyl methyl GSL. The dominant GSL types varied within the subspecies (Table 2.5) although the total GSL concentrations were similar (Table 2.6). B. carinata and B. nigra entries had simple profiles dominatedby 2-propenyl GSL and a similar range in total GSL concentration was evident in the two species. In B. júncea, while 2-propenyl GSL was the major GSL detected, significant levels of 3-butenyl GSL and 4-pentenyl GSL were also present in some entries.

However, unlike B. napus and B. campestris, the OH-substituted forms of these alkenyl GSL were not present in appreciable quantities in B. júncea. B. carinata and B. nigra entries contained minimum 2-propenyl GSL concentrations of 10 µmol g^{-1}, while some *B. júncea* entries had concentrations as low as 0.1 µmol g^{-1}.

S. alba and weed species tended to have relatively simple profiles dominated by one or two GSLs in high concentrations. *S. alba, S. arvensis* and *D. tenuifolia* had high concentrations of the aromatic GSLs, benzyl GSL and p-hydroxybenzyl GSL, which were absent from the shoots of the Brassica species. *B. tornefortii, B. fruticulosa* and *S. orientale* were dominated by 3-butenyl GSL while the latter also contained 3-methylthiopropyl GSL, which was not found in appreciable quantities in any of the other entries. Despite the high concentrations of the individual aliphatic and aromatic GSLs in the weed species, the concentration of the indolyl forms was low. Entries containing total GSL concentrations >20 µmol g^{-1} were represented in *B. napus oleifera biennis*, *B. carinata, B. nigra, B. juncea, S alba* and all of the weed species, although the ranges within species were large (Table 2.6). Maximum total GSL concentrations in *B. napus oleifera annua*, *B. campestris* and *B. oleracea* were <15 µmol g^{-1}. In all *B. napus*, *B. campestris* and *B. oleracea* species only ~50% of the total GSLs were ITC liberating, while for *B. nigra, B. juncea, B. carinata,* *S. alba* and the weed species almost all of the GSLs contained in the plant were ITC liberating (Table 2.6).

Table 2.5

Glucosinolates identified in Brassica samples, their HPLC retention times and major hydrolysis products (Kirkegaard & Sarwar (1998))

Number	Chemical name	Trivial name	Retention time (min)	Hydrolysis products
		Aliphatic		
1	3-Methylthiopropyl	Glucoibervcrin	16.80	ITC, ш triles
2	3-Metbylsiilplimylpropyl	Ghicoberin	7.27	ITC. nitriles
3	2-Propeuyl	Sinigrin	12.53	ITC. nitriles
4	4-Metbylthiobutyl	Glucoerusin	19.79	ITC, nitriles
	4-MethyIsulphinyIbutyI	Glucoraphanin	13.51	ITC. nitriles
6	3-Butcuyl	Gtucoiiapin	16.52	ITC. nitriles
7	2-Hydroxy-3-butenyl	Progoitnn	9.51	Oxazolidinc-2-thioncs
8	5-Metkylsulpliinylpentyl	Glucoalyssiu	11.96	ITC. nitriles
9	4-Puiienyl	Glucobiassicanapin	18.83	ITC. nitriles
10	2-Hydroxy-4-pcntcnyl	Gluconapoleiferin	15.24	Oxazol idine-2-thiones
		Aromatic		
II	2-Phenylethyl	Ghiconastiirtiin	21.42	ITC
12	2-Hydroxy-2-pheuylethyl	Glucobaibaiiii	17.82	ITC
13	Benzyl	Glucotropneokn	19.11	ITC
14	p-Hydioxybeiizyl	Ghicosiaalbin	15.58	ITC
		Itidolil		
15	3-Itidolylinetbyl	Glucobiassicin	20.20	Iudolyl-3-caibiool
16	4-Hydroxy-3-uidolyhnethyl	4-Hydioxyglucobrassicin	17.56	Tliioc valíate
17	4-Methoxy-3-indolylmethyl	4-N lethoxyghicobrassic m	2104	Auxins?
18	1-Meiboxy-3-ilklolylmethyl	Neoglucobrassicui	23.09	Pbytoalexins?

Table 2.6

Range in the concentration of individual glucosinolates ($\mu mol\ g^{-1}$) found in shoots of field grown Brassica and related species at flowering. Glucosinolates are numbered as in Table 2.4 (Kirkegaard & Sarwar, 1998)

Species	No. of entries	Aliphatic 2	3	5	6	7	9	10	Aromatic 11	Indolyl 15	16	17	18
B. napus oleifera													
biennis (oil)	6	–	–	0.2–0.3	0.5–3.3	1.6–9.2	0.8–7.8	0.6–1.9	0.6–2.3	0.2–0.4	–	0.1	0.1–0.3
biennis (fodder)	7	–	–	0.5–0.8	0.3–8.7	0.5–5.9	0.5–4.5	0.8–2.9	0.4–0.9	0.1–0.6	0.1	0.1	0.1–0.4
annua	7	–	–	0.1–0.5	0.1–0.8	0.2–3.8	0.1–1.8	0.1–1.5	0.1–1.3	0.1–0.6	0.1	0.1	0.1
B. napus rapifera	3	–	–	–	0.4–0.6	0.5–5.1	0.6	0.5–3.7	0–1.4	0.1–0.4	–	–	0.1–0.4
B. campestris oleifera													
biennis	1	–	–	–	1.6	1.7	3.8	1.8	1.6	0.2	0.1	–	–
annua	5	–	–	–	0.4–1.3	0.4–3.0	1.3–3.8	1.1–5.6	0.8–3.6	0.2–1.7	0.1–0.5	0.1–0.3	0.1–0.5
B. campestris rapifera	5	–	–	–	0.7–4.0	0.9–4.6	1.9–6.5	1.1–2.1	0.6–1.7	0.1–0.2	0.1	–	0.1–0.3
B. oleracea													
var. *gemmifera*	1	2.2	1.3	1.0	0.5	0.5	–	–	–	2.9	0.2	–	0.3
var. *capitata*	1	3.2	1.3	–	–	–	–	–	–	3.0	0.1	0.1	0.6
var. *botrytis*													
sv. *cauliflora*	1	1.4	–	–	–	–	–	–	–	1.6	0.1	0.7	3.2
sv. *cymosa*	1	–	–	2.4	–	–	–	–	–	1.3	–	0.1	4.1
var. acephala	2	1.4–1.5	2.2–3.2	0.5–1.1	0.5–1.6	0–1.4	–	–	–	3.1–4.0	0.2–0.3	–	1.0–1.1
B. carinata	6	–	10.0–20.2	–	–	–	–	–	–	0.4–0.9	0–0.1	–	0–0.1
B. nigra	5	–	10.7–26.4	–	–	–	–	–	0.3–0.4	0.1	–	–	–
B. juncea	14	–	0.1–18.7	–	0–7.5	–	0.1–2.0	0.1–0.3	0–1.3	0–0.2	0–0.1	–	0.1–0.2

Species	No. of entries	Aliphatic 1	5	6	7	8	9	10	Aromatic 11	13	14	Indolyl 15	16	17	18
S. alba	5	–	–	–	0.4–0.5	–	1.0–3.4	–	0.3–0.4	1.9–9.6	9.0–14.4	0–0.1	–	–	0–0.1
E. sativa	1	–	4.4	–	–	–	–	–	–	–	–	0.5	–	–	
B. fruticulosa	1	–	–	33.8	–	–	–	0.6	0.4	–	–	–	–	–	–
B. tournefortii	1	–	–	34.8	–	0.8	0.7	–	0.9	–	–	–	–	0.1	–
S. orientale	1	13.2	–	30.2	–	–	–	–	–	–	–	–	1.5	–	–
S. arvensis	1	–	–	–	0.6	–	–	–	1.4	–	15.3	–	–	0.7	1.6
D. tenuifolia	1	–	8.1	1.2	–	–	–	–	1.1	12.0	–	2.1	0.7	0.5	–

LSD's ($P < 0.05$) for individual glucosinolate concentrations: 3 – 1.0; 5 – 3.4; 6 – 2.1; 9 – 1.2; 10 – 0.4; 11 – 0.6; 15 – 0.2; 16 – 0.1; 17 – 0.5; 18 – 0.5.

(–) = not detected (<0.01 $mol\ g^{-1}$).

It was also found (Kirkegaard & Sarwar, 1998) that in contrast to the shoots, the roots of all Brassica species contained significant concentrations of aromatic GSLs, predominately 2-phenylethyl GSL (Tables 2.7 and 2.8). Significant quantities of benzyl GSL and fbhydroxybenzyl GSL were also present in the roots, while they were not detected in the shoots. In common with the shoots, indolyl GSLs were ubiquitous but in low concentrations (<2 μmol g^{-1}). Aliphatic GSLs were present in appreciable quantities in most species, and in general the profile in the shoots and roots was similar (Tables 2.5 and 2.7). As for the shoots, the concentrations of individual GSLs varied within species by two to ten fold (Table 2.7) while total GSLs in roots varied by two to five fold (Table 2.8). These differences within species were significant based on the LSDs constructed from the representative entry selection (Tables 2.7 and 2.8).

B. napus profiles were dominated by 2-phenylethyl GSL although significant quantities of the aliphatic GSLs found in the shoots (3-butenyl GSL, 4-pentenyl GSL and their OH-substituted forms) were also present. Although the maximum concentrations of some individual aliphatic GSLs were similar in the roots and shoots (e.g. 3-butenyl GSL, 4-pentenyl GSL) (Tables 2.5 and 2.7), total aliphatic GSL concentrations were generally higher in the shoots (see Tables 2.6 and 2.8). Consistent with the shoots, the maximum observed concentrations of individual and total root GSLs within *B. napus* sub-species followed the pattern biennis > rapifera > annua, although the range within sub-species was considerable.

In common with their shoot GSL profiles, *B. napus* oleifera annua and B. campestris oleifera had similar root profiles although 3-butenyl GSL and 2-hydroxy-3-butenyl GSL were absent from the latter. *B. campestris* spp. *rapifera* had significantly higher individual and total concentrations of aliphatic GSLs in the roots than ssp. *oleifera*.

B. oleracea vegetables had similar profiles of aliphatic GSLs in roots and shoots, lower concentrations of indolyl GSLs in the roots but higher levels of the aromatic 2-phenylethyl GSL.

As for *B. napus* and *B. campestris*, 2-phenylethyl GSL was the dominant GSL found in the roots of *B. carinata, B. nigra* and *B. juncea*. These species also had significant concentrations of 2-propenyl GSL in their roots although the maximum concentrations were approximately half of that found in the shoots (Tables 2.5 and 2.7). Consistent with shoots, 3-butenyl

GSL was also found in the roots of some *B. juncea* entries. The low levels of 2-propenyl GSL observed in the shoots of double low *B. juncea* lines were also observed in the roots, some of which had no detectable level present (Table 2.7, Figure 2.9).

Table 2.7

Range in concentration of glucosinolate classes found in the shoots of field grown Brassica and related species at flowering (Kirkegaard & Sarwar, 1998)

Species	No. of entries	Glucosinate concentration (μmol g^{-1})				Total ITC liberating
		Total aliphatic	Total aromatic	Total indolyl	Total	
B. napus oleifera						
biennis (oil)	6	3.5-22.2	0.6-2.3	0.2-0.6	4.6-23.8	1.9-12.3
biennis (fodder)	7	4.1-17.2	0.4-0.9	0.1-0.7	5.5-18.3	1.3-12.8
annua	7	0.1-8.4	0.0-1.3	0.0-0.7	0.2-10.4	0.1-4.4
ssp. *rapifera*	3	1.0-10.0	0.0-1.4	0.2-0.8	1.2-12.2	0.1-2.6
B. campestris oleifera						
biennis	1	8.4	1.6	0.3	10.3	7.0
annua	5	3.4-8.6	0.8-3.6	0.3-2.5	5.3-14.7	2.8-7.0
ssp. *rapifera*	5	6.4-13.4	0.6-1.7	0.2-0.6	7.8-15.5	3.6-9.7
B. oleracea						
var. *gemmifera*	1	5.5	-	3.4	8.9	5.0
var. *capitata*	1	4.5	-	3.8	8.3	4.5
var. *botrytis*						
svar. *cauliflora*	1	1.4	-	5.6	7.0	1.4
svar. *cymosa*	1	2.4	-	5.5	7.9	2.4
var. *acephala*	2	4.7-8.7	-	4.5-5.2	9.2-13.9	4.7-7.3
B. carinata	6	10.0-20.2	-	0.3-0.9	10.5-21.1	10.0-20.2
B. nigra	5	10.7-26.4	0.0-0.4	0.0-0.1	11.2-26.4	11.1-26.4
B. juncea	14	1.1-20.5	0.0-1.3	0.1-0.4	1.4-21.7	1.2-21.6
S. alba	5	1.4-3.8	12.6-24.0	0.0-0.1	15.8-25.6	15.7-25.6
E. sativa	1	4.4	-	0.5	4.9	4.4
B. fruticulosa	1	34.3	0.5	0.3	35.1	34.2
B. tournefortii	1	36.3	0.9	0.1	37.3	37.2
S. orientale	1	43.4	-	1.5	44.9	43.4
S. arvensis	1	0.6	16.8	2.3	19.7	17.4
D. tenuifolia	1	9.3	13.0	2.8	25.1	21.7
LSD ($P < 0.05$)		3.2	5.3	0.3	6.6	*4.3*

(-) = not detected (<0.01 fimol g^{-1}).

Table 2.8

Range in the concentration of individual glucosinolates (µmol g flowering. Glucosinolates are numbered as in Table 3) found in roots of field grown Brassica and related species (Kirkegaard & Sarwar, 1998)

Species	No. of entries	Aliphatic 2	3	5	6	7	9	10	Aromatic 11	13	Indolyl 15	16	17	18
B. napus oleifera														
biennis (oil)	6	–	–	0.4–0.7	0.4–1.0	0.3–3.7	0.4–4.4	0.7–2.6	7.9–19.3	1.0–2.7	0.3–0.5	–	0.2–0.7	0.1
biennis (fodder)	7	–	–	0.5–0.9	0.7–10.2	1.3–5.0	0.6–7.5	0.8–2.0	7.1–19.5	1.0–3.4	0.2–1.1	–	0.4–1.1	0.1–0.4
annua	7	–	–	0.1–0.8	–	0.3–0.7	0.4	0.5–1.5	2.3–11.6	0.2–1.3	0.2–0.4	0.1	0.2–0.4	0.1–0.4
B. napus rapifera	3	–	–	–	–	0.6–1.4	–	0.6–1.6	1.5–12.8	0.4–1.3	0.3–0.7	0.1–0.2	0.1–0.2	0.2–1.1
B. campestris oleifera														
biennis	1	–	–	–	–	–	0.3	0.6	9.4	–	0.3	–	0.4	0.3
annua	5	–	–	–	–	–	0.3	0.4–0.6	2.1–9.0	0.2	0.2–0.4	0.1–0.8	0.2–0.8	0.2–1.0
B. campestris rapifera	5	–	–	–	0.3–2.0	0.3–4.5	0.5–2.7	0.9–1.8	7.1–11.9	–	0.2–0.6	–	0.1–0.2	0.1–0.5
B. oleracea														
var. *gemmifera*	1	0.3	1.2	0.4	0.7	0.5	–	–	2.5	–	0.1	0.3	0.1	0.3
var. *capitata*	1	1.3	6.2	–	–	–	–	–	3.3	–	0.5	2.0	0.5	0.4
var. *botrytis*														
sv. *cauliflora*	1	0.7	–	–	–	–	–	–	1.7	–	0.7	0.8	0.7	1.1
sv. *cymosa*	1	–	–	1.5	0.3	0.3	–	–	3.1	–	0.2	0.2	0.2	0.4
var. *acephala*	2	0.3	1.1–2.3	0.6–0.8	0.4	0–0.9	–	–	4.7–5.2	2.2–3.0	0.2–0.4	0.6–0.7	0.2–0.4	0.3–0.4
B. carinata	6	–	2.2–10.4	–	0–0.4	0–1.0	–	–	3.9–12.2	–	0.1–0.4	0–0.2	0.1–0.4	0.1–0.6
B. nigra	5	–	0.5–5.1	–	–	–	–	–	0.9–8.8	–	0–0.1	0–0.2	0.1–0.4	0–0.1
B. juncea	14	–	0–4.8	–	0–1.9	–	0–0.5	–	2.5–12.5	0–0.6	0–0.9	0–0.2	0.1–1.1	0–0.7

Species	No. of entries	Aliphatic 2	5	6	7	8	Aromatic 11	13	14	Indolyl 15	16	17	18
S. alba	5	0–0.2	0.9–1.7	–	0–0.4	0–0.7	2.1–4.1	2.0–5.3	2.7–3.9	0–0.2	–	0.1–0.9	0.2–1.2
E. sativa	1	–	0.7	–	–	–	1.8	–	–	–	–	–	–
B. fruticulosa	1	–	–	12.9	–	1.9	18.5	–	–	0.5	–	0.3	0.4
B. tournefortii	1	–	–	21.7	–	7.1	26.4	–	–	–	–	0.3	–
S. orientale	1	–	–	13.7	–	–	25.7	–	5.3	0.7	–	0.8	1.3
S. arvensis	1	–	–	–	0.9	–	19.0	–	23.1	–	0.2	–	0.1
D. tenuifolia	1	–	14.7	–	–	–	1.7	50.0	2.0	0.5	–	–	–

LSD's for individual glucosinolate concentrations: 5 – 1.5; 6 – 1.1; 8 – 1.0; 11 – 2.3; 13 – 3.6; 14 – 0.4; 15 – 0.1;17 – 0.2; 18 – 0.2
(–) = not detected (<0.01 μmol g^{-1}).

In *S. alba* and the weed entries, the dominant GSLs found in shoots also dominated in roots, but as for all the other species, this was in association with high levels of 2-phenylethyl GSL. In some species the concentrations of individual GSLs were higher in the roots than the shoots (e.g. D. tenuifolia, S arvensis). The high concentration of 3-butenyl GSL in the shoots of B. fruiticulosa, S orientale and B. tournefortii were also present in roots, along with similarly high concen- trations of 2-phenylethyl GSL. The roots of the weed species contained the highest concentrations of both individual and total GSLs measured in the study. A greater portion of the total root GSLs were ITC liberating compared to the shoots due to the dominance of 2-phenylethyl GSL in the roots (Table 2.8).

Significant positive correlations between total root and total shoot GSL concentrations were only found within B. napus and B. carinata entries (bothr2 = 0.81) while there were neither significant nor consistent correlations within the other species. There was a significant ($P < 0.05$) positive correlation between total seed and total shoot GSL concentration for the 65 entries for which seed was collected, although the relationship accounted for only 22% of the variation. There were no significant or consistent relationships within species, with the exception of B. juncea where seed GSL and shoot GSL were positively correlated ($r^2 = 0.56$).

There was no relationship between seed GSL concentration and root GSL concentration generally, or within any of the individual species. GSL production on a ground area basis (mmol m^{-2}) is the product of the biomass and GSL concentration of a particular tissue and is shown for shoot and root tissues and whole plants for individual entries in Figure 2.10. Isolines of GSL production on a ground area basis are shown for combinations of GSL concentration and biomass production.

In shoot tissues (Figure 2.10 a) there was large variation in GSL production both within and between species. High shoot GSL production (>20 mmol m^{-2}) arose from high biomass (e.g. *B. oleracea*), from high GSL concentration (e.g. *B. napus oleífera biennis*) or from combinations of moderate to high levels of each (e.g. *B. nigra*).

Table 2.9

Range in concentration of glucosinolate classes and total glucosinolates found in the roots of field grown Brassica and related species at flowering (Kirkegaard & Sarwar, 1998)

Species	No. of entries	Glucosinate concentration (μmol g^{-1})				
		Total aliphatic	Total aromatic	Total indolyl	Total	Total ITC liberating
B. napus oleifera						
biennis (oil)	6	1.8-12.1	8.9-21.4	0.3-1.2	11.5-33.9	9.7-27.0
biennis (fodder)	7	4.6-21.7	9.0-21.3	0.7-2.2	20.7-34.9	13.8-29.7
annua	7	0.1-3.2	2.5-12.5	0.5-1.2	3.2-15.9	2.7-13.7
ssp. *rapifera*	3	1.2-3.0	1.9-14.1	0.6-2.2	3.7-19.3	1.9-14.1
B. campestris oleifera						
biennis	1	0.9	9.4	1.0	11.3	9.7
annua	5	0.0-0.9	2.1-9.4	0.7-1.9	3.8-11.3	2.1-9-.0
ssp. *rapifera*	5	2.8-8.5	7.1-11.9	0.6-0.9	13.2-21.2	8.3-14.8
B. oleracea						
var. *gemmifera*	1	3.1	2.5	0.8	6.4	5.1
var. *capitata*	1	7.5	3.3	3.4	14.2	10.8
var. *botrytis*						
svar. *cauliflora*	1	0.7	1.7	3.3	5.7	2.4
svar. *cymosa*	1	2.1	3.1	0.9	6.1	4.9
var. *acephala*	2	2.6-4.5	6.9-8.2	1.3-1.9	12.1-13.3	10.5-10.8
B. carinata	6	2.2-10.9	3.9-12.2	0.5-1.2	8.0-24.3	7.1-23.1
B. nigra	5	0.5-5.1	0.9-8.8	0.2-0.6	4.0-11.1	1.4-10.5
B. juncea	14	0.4-4.8	2.5-12.8	0.1-1.2	4.6-14.5	4.1-11.9
S. alba	5	0.9-2.4	7.1-12.3	0.3-1.9	8.8-16.5	8.0-14.7
E. sativa	1	0.7	2.5	nd	3.2	2.5
B. fruticulosa	1	14.8	18.6	1.0	34.4	33.5
B. tournefortii	1	28.8	26.4	0.3	55.5	55.2
S. orientale	1	13.7	31.0	2.8	47.5	44.7
S. arvensis	1	0.9	42.1	0.3	43.3	43.0
D. tenuifolia	1	14.7	53.6	0.6	68.9	68.2
LSD ($P < 0.05$)		2.7	3.3	0.2	4.9	3.7

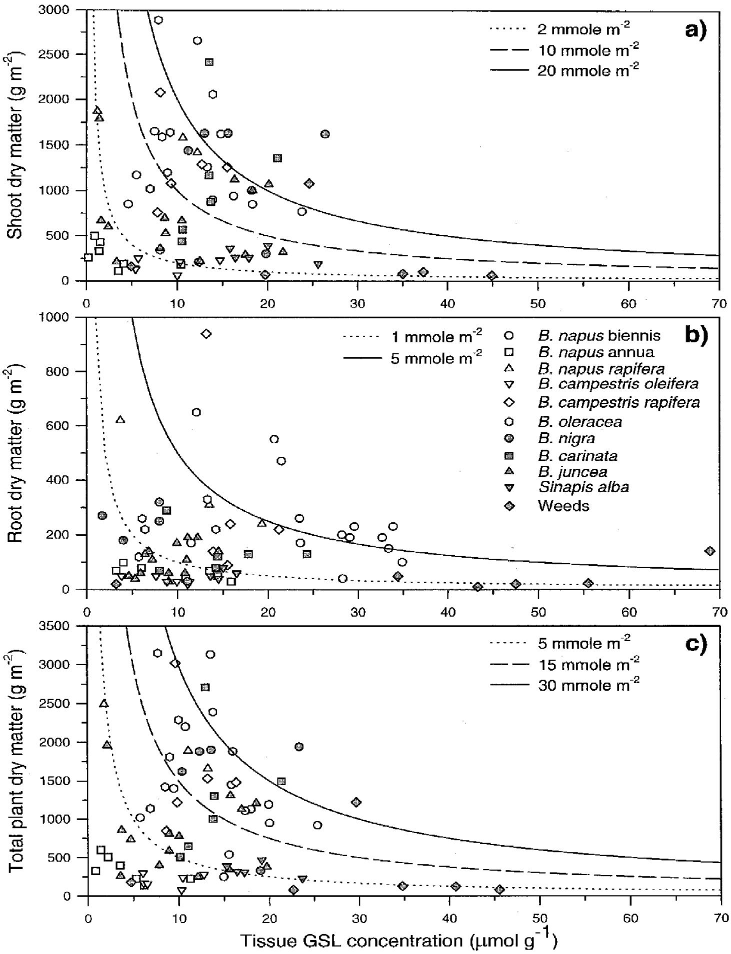

Figure 2.10 – Relationship between tissue glucosinolate concentration and biomass for (a) shoot tissue, (b) root tissue and (c) total plant for Brassica and related weed species.

(O) *B. napus oleifera biennis*, (□) *B. napus oleifera annua*, (Δ) *B. napus rapifera*, (v) *B. campestris oleifera* (>) *B. campestris rapifera*, (O) *B. oleracea*, (•) *B. nigra*, (■) *B. carinata*, (a) *B. juncea*, (▼) *S. alba*, (♦) weed species. (Kirkegaard & Sarwar, 1998)

Despite the large variation some general patterns emerged. All of the *B. napus oleifera annua* and *B. campestris oleifera* entries had shoot GSL production which fell on or below the 2 mmol m^{-2} isoline while no other species had all entries in this low category. All of the other species, with the exception of *S. alba*, had entries with >10 mmol m^{-2} and six species had entries with >20 mmol m^{-2}. There was no significant correlation found between shoot biomass and shoot GSL concentration in any of the species, indicating that high biomass production did not lead to a dilution of GSL concentration, although no entries had both high GSL concentration and high biomass

It is proved (Kirkegaard & Sarwar, 1998) that GSL production in roots was lower than that of shoots primarily due to the lower root biomass, while the range in GSL concentrations in roots and shoots was similar (Figure 2.10 a, b). High levels of root GSL production resulted from high biomass in some entries (e.g. *B. campestris rapifera*) and from high glucosinolate concentration in others (e.g. *D. tenuifolia*), while most of the *B. napus oleifera biennis* combined moderate to high levels of biomass and GSL concentration. GSL production of all *B. napus oleifera annua*, *B. campestris oleifera* and *S. alba* entries fell below the 1 mmol m^{-2} isoline while *B. napus oleifera biennus* entries were predominately above the 5 mmol m^{-2} isoline. The entries of the other species/subspecies fell into the low (<1 mmol m^{-2}) or moderate (<5 mmol m^{-2}) categories. Despite the high GSL concentrations found in weed species, low root biomass resulted in low levels of GSL production with the exception of *D. tenuifoli*a which fell into the > 5 mmol m^{-2} category. Interestingly, there were significant ($P < 0.05$) negative correlations between root biomass and root GSL concentrations in B. napus oleifera annua ($r^2 = 0.47$), and *B. campestris oleifera* ($r^2 = 0.75$), the two species with the lowest GSL concentrations, but no significant relationships within any of the other species.

It also indicates (Kirkegaard & Sarwar, 1998) that the pattern of total plant GSL production generally followed that of the shoots due to the relatively large contribution of the shoots to total plant biomass (Figure 1c). All entries of *B. napus oleifera annua* and *B. campestris oleifera* produced <5 mmol m^{-2} GSL, as did several of the *B. juncea* entries, and the *S. alba* entries fell just above the 5 mmol m-2 isoline. Entries from all other species were distributed within the 530 mmol m^{-2} range. Entries from

B. napus oleifera biennis, *B. campestris rapifera, B. oleracea, B. nigra, B. carinata* were represented in the > 30 mmol m^{-2} category along with the weed species *D. tenuifolia*. The ranking of entries for total plant GSL production changed when only the ITC liberating GSLs were considered (Figure 2.11). Only half of the total GSLs present in *B. napus, B. campestris* and *B. oleracea* species yield ITCs upon hydrolysis due primarily to significant concentrations of OH-substituted aliphatic GSLs (GSL 7, 10) or indolyl GSLs in their tissues, which do not yield ITCs upon hydrolysis (Table 2.3). Despite several entries within these species producing high total GSLs, only one entry produced >20 mmol m-2 of ITC liberating GSL (Figure 2.10). In contrast, *B. nigra, B. carinata, B. juncea, S. alba* and the weeds species contained predominately ITC liberating GSLs and consequently several entries within these species produced >20 mmol m^{-2} of ITC liberating GSLs.

The results of this study illustrate the need to consider the contribution of root GSLs to the sup-pressive potential of green manure crops and as the principal contributor in rotation or companion crops where shoot material is not incorporated. The universal presence of 2-phenylethyl GSL in significant concentrations in the roots of brassicas raises questions regarding its function. The ITCs produced by hydrolysis of aromatic glucosinolates such as 2-phenylethyl are generally less volatile than aliphatic types and may therefore persist for longer in the soil.

This persistence may have provided greater suppression of soil-borne pests, pathogens and weeds and led to selection pressure for higher levels of aromatic types in root tissues in the same way that selection for particular GSLs from pest pressure in the aerial environment has lead to selection for specific aliphatic types in the leaves (Mithen et al., 1995).

Relatively little is known about the activity of 2-phenylethyl ITC in the soil since many previous studies have concentrated on aliphatic types such as methyl ITC (a commercial soil fumigant) or 2-propenyl ITC (allyl) due to its early recognition as the active constituent of mustard oils. However 2-phenethyl ITC has been shown to be significantly more toxic than 2-propenyl ITC in vitro to fungi (Drobnica et al., 1967; Sarwar et al., 1998), insects (Borek et al., 1995) and germinating wheat seeds (Bialy et al., 1990). The predominance in roots of the aromatic GSLs, particularly 2-phenylethyl GSL revealed in this study suggests that their activity and persistence in soil warrant further investigation.

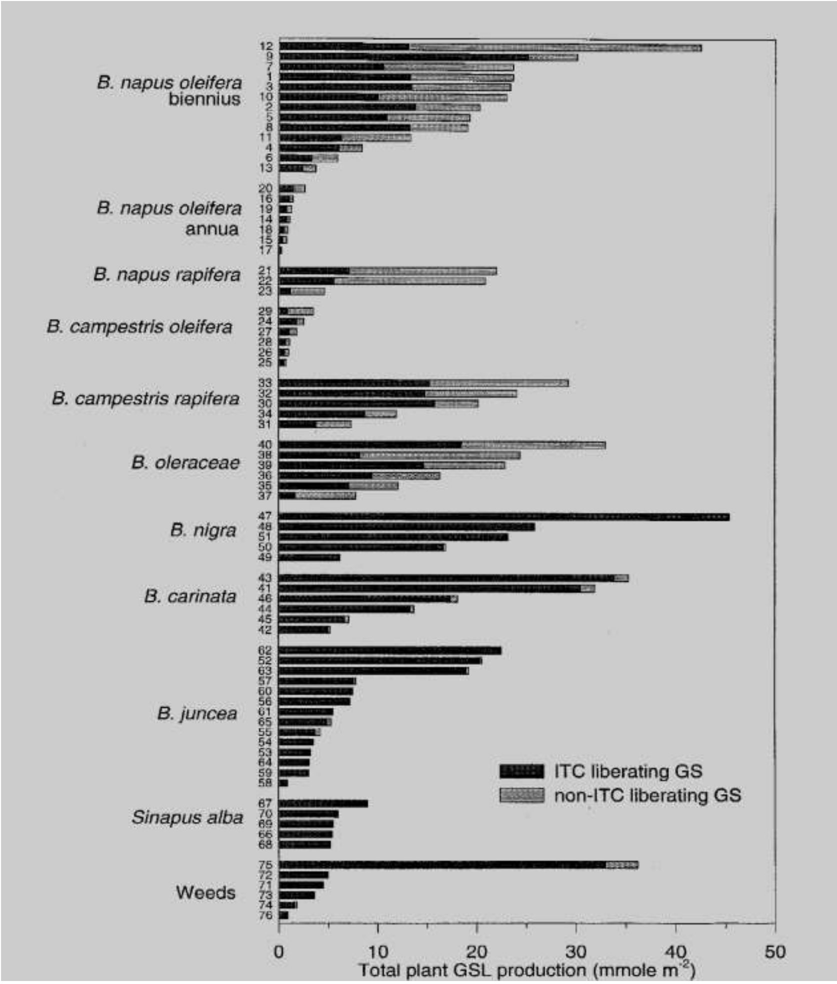

Figure 2.11 – Proportion of total plant glucosinolate production (root + shoot) comprised of ITC liberating (dark bar) and non-ITC liberating (light bar) glucosinolates for 76 Brassica and related species at mid-flowering. Individual entries are numbered as in Table 2.3 (Kirkegaard & Sarwar, 1998)

Brown et al. (1991) have estimated that the amount of methyl ITC used commercially for soil sterilization ranges from 517 to 1294 nmol g^{-1} of soil depending upon the specific crop and control required. The maximum total plant GSL at mid-flowering measured in this experiment was 45.3 mmol m^{-2} which is equivalent to 324 nmol g^{-1} of soil assuming a soil bulk density of 1.4 g cm^{-3} and incorporation to 10 cm. In a subsequent spring-sown experiment at the same site, GSL production was doubled in some entries (Part II, Sarwar and Kirkegaard, 1998). The potential production of ITCs by hydrolysis of GSLs in brassicas (up to 700 nmol g^{-1}) is therefore in a range likely to contribute to pathogen suppression, considering that commercial rates of methyl ITC are aimed at total control.

The effectiveness of brassicas for biofumigation will ultimately depend on many factors beside the BP of the particular Brassica used. The timing of incorporation or exudation of the GSL containing tissue must coincide with a susceptible stage in the life cycle of the pest organism and the suppression must persist to provide protection for the crop of interest. In addition, effectiveness of biofumigation will be influenced by efficiency of incorporation, activity of the hydrolysing myrosinase enzyme, and losses due to volatilisation, sorption onto clay and organic matter, leaching, and microbial degradation (reviewed by Brown and Morra, 1997).

The diversity of GSL profiles, concentrations and production within and between Brassica and related species demonstrated in this experiment suggest that where pest or disease suppression by Brassica rotation or green manure crops can be linked to GSL hydrolysis products, opportunities will exist to select or develop brassicas with enhanced biofumigation potential. In addition to the existing genetic variation in glucosino-late production demonstrated here, further genetic manipulation of glucosinolate concentration, profile and distribution is possible using wide crossing (e.g. Gia-moustris and Mithen, 1995), interspecific crosses (e.g. Chopra et al., 1996) and molecular genetic techniques (Mithen and Campos, 1996).

As for the biochemical composition of oil radish in its synonymous name, according to the research of Ricardo et al. (2018), which is cited in the author's version, the biochemical composition of the aboveground mass of oil radish is as follows:

– phytosterols в-sitosterol (1);

– stigmasterol (2) and />-sitosterol-3-/>-O-D-glucopyranoside;

– D-glucose based on 13C NMR spectra [102.0 (C-1'), 74.5 (C-2'), 77.5 (C-3'), 71.1 (C-4'), 77.1 (C-5'), 62.4 (C-6')];

– norisoprenoid dehydrovomifoliol;

– S-(+)-de-hydrovomifoliol;

– flavonoids kaempferol 3-O-a-L-rhamnopyranosyl-7-O-a-L-rhamnopyranoside and quercetin 3-O-a-L-rhamnopyranosyl-7-O-a-L-rhamnopyranoside, respectively;

– phenylpropanoid ferulic acidm;

– sitosterol (1) (1H NMR (500 MHz, CDCl3) 5: 3.53 (1H, m, H-3), 5.36 (1H, dl, J = 4.0 Hz, H-6), 0.68 (3H, sl, H-18), 1.01 (3H, sl, H-19), 0.92 (3H, d, J = 6.4 Hz, H-21), 0.83 (3H, d, J = 6.5 Hz, H-26), 0.80 (3H, sl, H-27). 13C NMR (75.45 MHz, CDCl3) 5: 37.4 (C-1), 32.1 (C-2), 72.0 (C-3), 42.4 (C-4), 140.9 (C-5), 121.9 (C-6), 32.1 (C-7), 32.1 (C-8), 50.3 (C-9), 36.3 (C-10), 21.2 (C-11), 39.9 (C-12), 42.2 (C-13), 56.9 (C-14), 24.5 (C-15), 28.4 (C-16), 56.2 (C-17), 12.0 (C-18), 19.6 (C-19), 36.3 (C-20), 18.9 (C-21), 34.1 (C-22), 26.2 (C-23), 46.0 (C-24), 29.3 (C-25), 19.6 (C-26), 19.2 (C-27), 23.1 (C-28), 12.2 (C-29));

– estigmasterol (2): 1H NMR (500 MHz, CDCl3) 5: 3.53 (1H, m, H-3), 5.36 (1H, dl, J = 4.0 Hz, H-6), 0.68 (3H, sl, H-18), 1.01 (3H, sl, H-19), 5.15 (1H, dd, J = 8.6/15.1 Hz, H-22), 5.01 (1H, dd, J = 8.6/15.1 Hz, H-23). 13C NMR (75.45 MHz, CDCl3) 5: 37.4 (C-1), 31.8 (C-2), 72.0 (C-3), 42.4 (C-4), 140.9 (C-5), 121.9 (C-6), 32.1 (C-7), 32.1 (C-8), 50.3 (C-9), 36.3 (C-10), 21.2 (C-11), 39.9 (C-12), 42.4 (C-13), 57.0 (C-14), 24.5 (C-15), 29.1 (C-16), 56.1 (C-17), 12.2 (C-18), 19.6 (C-19), 40.7 (C-20), 21.2 (C-21), 138.5 (C-22), 129.4 (C-23), 51.4 (C-24), 32.1 (C-25), 21.3 (C-26), 19.1 (C-27), 25.6 (C-28), 12.2 (C-29);

– daucosterol (3): 13C NMR (75.45 MHz, CD3OD) 5: 38.1 (C-1), 30.3 (C-2), 79.6 (C-3), 39.3 (C-4), 141.2 (C-5), 122.6 (C-6), 32.7 (C-8), 51.1 (C-9), 37.4 (C-10), 21.8 (C-11), 40.6 (C-12), 43.0 (C-13), 57.6 (C-14), 24.9 (C-15), 28.9 (C-16), 56.9 (C-17), 12.2 (C-18), 19.7 (C-19), 36.9 (C-20), 19.2 (C-21), 34.7 (C-22), 26.7 (C-23), 46.7 (C-24), 29.9 (C-25), 19.3 (C-26), 20.1 (C-27), 23.7 (C-28), 12.2 (C-29), 102.0 (C-1'), 74.5 (C-2'), 77.5 (C-3'), 71.1 (C-4'), 77.1 (C-5'), 62.4 (C-6');

– S-(+)-Dehydrovomifoliol (4): [a]D = +98, 1H NMR (300 MHz, CDCl3) 5: 2.33 (1H, d, J = 15.0 Hz, H-2a), 2.50 (1H, d, J = 15.0 Hz, H-2b), 5.95 (1H, qt, J =1.5 Hz, H-4), 6.83 (1H, d, J = 15.0 Hz, H-7), 6.46 (1H, d, J = 15.0 Hz, H-8), 2.3 (3H, s, H-10), 1.88 (3H, d, J = 1.5 Hz, H- 11), 1.02 (3H, s, H-12), 1.10 (3H, s, H-13). 13C NMR (75.45 MHz, CDCl3) 5: 41.6 (C-1), 49.7 (C-2), 197.1 (C-3), 128.0 (C-4), 160.5 (C-5), 79.5 (C-6), 145.1 (C-7), 130.5 (C-8), 197.6 (C-9), 28.6 (C-10), 18.8 (C-11), 24.5 (C-12), 23.1 (C-13);

– Kaempferol 3,7-rhamnoside (5): 1H NMR (300 MHz, CD3OD) 5: 6.68 (1H, d, J = 2.4 Hz, H-6), 6.42 (1H, d, J = 2,4 Hz, H-8), 7.76 (2H, d, J = 8.7 Hz, H-2'/6'), 6.92 (2H, d, J = 8.7 Hz, H-3'/5'), 5.54 (1H, d, J = 1.2 Hz, H-1»), 4.22 (1H, m, H-2»), 3.28-3.90 (1H, H-3»), 3.32 (1H, m, H-4»), 4.02 (1H, m, H-5»), 1.25 (3H, d, J = 6.3 Hz, CH3), 5.38 (1H, d, J = 1.5 Hz, H-1»), 3.28-3.90 (1H, H-3»'), 3.47 (1H, m, H-4»'), 3.59 (1H, m, H-5»), 0.92 (3H, d, J = 5.7 Hz, CH3). 13C NMR (75.45 MHz, CD3OD) 5: 159.7 (C-2), 136.4 (C-3), 179.7 (C-4), 162.9 (C-5), 95.5 (C-6), 163.4 (C-7), 99.8 (C-8), 122.3 (C-1'), 131.9 (C-2'/6'), 116.5 (C-3'/ 5'), 161.7 (C-4'), 100.5 (C-1»), 71.8 (C-2»), 72.0 (C-3»), 73.5 (C-4»), 71.6 (C-5»), 18.0 (CH3), 103.4 (C-1»), 72.0 (C-2»), 72.0 (C-2»), 73.1 (C-4»), 71.2 (C-5»), 17.6 (CH3);

– Quercetin 3,7-rhamnoside (6): 1H NMR (300 MHz, CD3OD) 5: 6.68 (1H, d, J = 2.4 Hz, H-6), 6.42 (1H, d, J = 2,4 Hz, H-8), 7.35 (1H, d, J = 2.1 Hz, H-2'), 6.88 (1H, d, J = 8.4 Hz, H-5'), 7.30 (1H, dd, J = 8.4, 2.1Hz, H-6'), 5.54 (1H, d, J = 1.2 Hz, H-1»), 4.22 (1H, m, H-2»), 3.28-3.90 (1H, H-3»), 3.32 (1H, m, H-4»), 4.02 (1H, m, H-5»), 1.25 (3H, d, J = 6.3 Hz, CH3), 5.38 (1H, d, J = 1.5 Hz, H-1»), 3.28-3.90 (1H, H-3»), 3.47 (1H, m, H-4»), 3.59 (1H, m, H-5»), 0.92 (3H, d, J = 5.7 Hz, CH3). 13C NMR (75.45 MHz, CD3OD) 5: 159.7 (C-2), 136.4 (C-3), 179.7 (C-4), 162.9 (C-5), 95.5 (C-6), 163.4 (C-7), 99.8 (C-8), 122.3 (C-1'), 131.9 (C-2'/6'), 116.5 (C-3'/5'), 161.7 (C-4'), 100.5 (C-1»), 71.8 (C-2»), 72.0 (C-3»), 73.5 (C-4»), 71.6 (C-5»), 18.0 (CH3), 103.4 (C-1»), 72.0 (C-2™), 72.0 (C-2»), 73.1 (C-4»), 71.2 (C-5»), 17.6 (CH3);

– ferulic acid (7): 1H NMR (300 MHz, D2O) 5: 7.25 (1H, sl, H-2), 6.92 (1H, d, J = 16,0 Hz, H-5), 7.13 (1H, dd, J = 1.2/8.1 Hz, H-6), 7.44 (1H, d, J = 16.0 Hz, H-7), 6.37 (1H, d, J = 16.0 Hz, H-8), 3.89 (3H, s, CH3). 13C NMR (75.45 MHz, D2O) 5: 130.6 (C-1), 114.0 (C-2), 150.5 (C-3), 149.8 (C-4), 118.5 (C-5), 125.5 (C-6), 146.0 (C-7), 121.9 (C-8), 177.1 (C-9), 58.8 (CH3).

In conclusion (Ricardo et al., 2018), the results showed that straw of the aerial parts of *Raphanus sativus* var. *oleifer* Stokes possess a phytotoxic activity, and that the dichloromethane fraction was the most active against *E. heterophylla*, *B. pilosa* and *I. grandifolia*. So, it can be concluded that the aerial parts of *R. sativus* possess phytotoxic compounds able to reduce the emergence and growth of weed species, properties that further support the benefit of its use as a cover plant.

A detailed assessment of the biofumigation potential of cruciferous plant species was made in the study by Santos et al. (2021), the results of which are consistently presented in Tables 2.10–2.15.

Clarkson et al. (2020) were noted that there are various reports of soilborne plant disease suppression through the use of biofumigant plants, some of which have been summarised by Matthiessen & Kirkegaard (2006) and Motisi et al., (2010) but some of the important groups of pathogens have been targeted including Aphanomyces, Fusarium, Gaumannomyces, Phytophthora, Pythium, Rhizoctonia, Sclerotinia and Vertcciiiium as well as species of endoparasitic and semi-endoparasitic nematodes such as Globodera, Meloidogne, Pratylenchus and Tylenchus. There has been less emphasis however regarding the effect of biofumigation on free-living nematode species. Overall, research concerning biofumigation for control of soilborne pathogens does not constitute a major area of work and there has been a lack of a consistent experimental approach. Hence, levels of control have varied considerably between different target organisms and different studies which highlights one of the major problems associated with adopting biofumigation commercially. It is clear however from in vttro studies that pathogens vary in their sensitivity to different ITCs (e.g. Brown and Morra, 1997; Smith and Kirkegaard, 2002) as do the susceptibility of different life cycle stages and structures such as spores, mycelium and sclerotia. It is clear therefore that different pathogens will require different biofumigants for effective control and further work is required to elucidate the best biofumigant(s) for specific disease problems.

Table 2.10

Promising experimental results obtained for the control of fungi using biofumigation with plant species of the Brassicaceae family (Santos et al., 2021)

Biofumigant	Target	Host	Strategy	Test type	Comments	Reference
Brassica oleracea	*R. solani*	Tomato	Use of fresh residues	Bioassay, greenhouse, field	Reduced symptoms and increased yield.	Tsror et al. (2007)
Various species	Various species	N/A	Powder	In vitro	Reduced *Ceratobasidium fimbriata* by 68.6% and *V. dahliae* by 68.7%.	Fan et al. (2008)
Brassica napus, B.juncea, B. campestris	Sclerotinia sclerotiorum	N/A N/A	Macerated and dry tissues	In vitro	Growth reduction and sclerotia formation.	Ojaghian et al. (2012)
N/A	*Sclerotium rolfsii, S. sclerotiorum*		Mustard synthetic essential oil	*In vitro,* field	Delayed sclerotia germination.	Dhingra et al. (2013)
B. juncea	*R. solani*	Sugar beet	Planting and incorporation	Field	Consistent control of primary infection.	Motisi et al. (2013)
Various species	*V. dahliae*	N/A	Residue incorporation	*In vitro,* field	*B. juncea* significantly reduced the number of viable microsclerotia.	Neubauer et al. (2014)
Various species	Various species	N/A	Dry powdered plants	In vitro	Released volatiles showed inhibitory effects.	Prasad et al. (2016)
Various species *B. carinata*	*S. sclerotiorum V. dahliae*	N/A N/A	Dry and ground residues *Pellets* (DSM), liquid formulation	*In vitro* *In vitro,* field	Effect on mycelial growth and germination. 67% efficiency using the liquid formulation.	WarmingtoN & Clarkson (2016) Wei et al. (2016)
B. juncea	*Sclerotinia homoeocarpa*	Grass	(DSM)	*In vitro,* field	Reduced mycelial growth and incidence.	Pan et al. (2017)
B. nigra, B. oleracea	*R. solani*	Potato	Leaf extract	*In vitro,* field	*B. nigra* was the most effective at inhibiting growth.	Rubayet et al. (2018)

N/A – Not applicable. DSM – defatted seed meals.

Table 2.11

Promising experimental results obtained in the control of *Fusarium* spp. using biofumigation with plant species of the Brassicaceae family (Santos et al., 2021)

Biofumigant	Target	Host	Strategy	Test type	Comments	Reference
B. oleracea	*Fusarium oxysporum*	N/A	Crushed residues	*In vitro*	Reduced the population of *F. oxysporum*.	Iriarte et al. (2011)
B. juncea, S. alba	*F. graminearum*	N/A	Crushed residues	*In vitro*	Suppressed the growth of *F. graminearum*.	Perniola et al. (2012)
B. juncea	*Fusarium* sp.	Bitter melon, calabash	Macerated leaves	Bioassay	Reduced mycelial growth and incidence. Biofumigation combined with	RelevantE & Cumagun (2013)
B. juncea	*F. graminearum*	N/A	Crushed residues	*In vitro*	*Trichoderma* spp. had a synergistic effect against the pathogen. Inoculum control	Perniola et al. (2014) Morales-Rodríguez et al. (2018)
B. carinata	*F. circinatum*	Pine	Pellets (DSM)	Bioassay	and reduced seed mortality.	
B. juncea, Diplotaxis tenuifolia	*F. oxysporum* f. sp. *cucumerinum*	Cucumber	Planting and incorpo-ration	Green-house	Suppressed *Fusarium* wilt.	Jin et al. (2019)
B. carinata	*Fusarium* spp.	Wheat	Planting and incorpo-ration	Field	Reduced incidence and severity; increased yield.	Campanella et al. (2020)

N/A – Not applicable. DSM – defatted seed meals.

Table 2.12

Promising experimental results obtained in the control of oomycetes using biofumigation with plant species of the Brassicaceae family (Santos et al., 2021)

Biofumigaiit	Target	Host	Strategy	Test type	Comments	Reference
Brassica júncea, lberis amara	*Pythium* spp.	NA	Dehydrated plants (pellets)	*In vitro*	After adding water, the dried plants showed ftmgitoxic activity against *Pythiwn* spp. Bioftimigation.	Lazzeri et al. (2004)
Brassica carinara	*Phytophrhora cactorum*	Strawberry	Residue incorporation	Field	combined with solarization reduced the occurrence of the pathogen and increased yield.	Barrau et al. (2009)
B. oleracea	Various species	Sweet pepper	Fresh residues – solanzalion	Field	Reduction of plants with symptoms and increased	VillaloboS el al. (2013)
B. napas	*Phytophrhora capsici*	Pepper	Ground seeds	Field	yield. Reduced incidence through changes in the structure of the soil microbial community.	Wang et al. (2014a)
B. napas	*P. capsici*	Pepper	Ground seeds	Bioassay	Reduced disease and increased bacterial	Wang el al. (2014b)
B. carínata	*P. citntantonti*	*Quercus cerris*	Pellets (DSM)	*In vitro,* bioassay	diversity in the soil. Inliibited mycelial growth and germination of	Morales-Rodríguez et al. (2016)
B. ca/inata, B. júncea, B. napus	*P cinnamotni*	Yellow lupin	Ground seeds	*In xitro,* bioassay	clilamydospores and zoospores, and reduced inoculum potential. *B. carinara* and *B. júncea* reduced mycelial growth aud decreased *P. cinnamonii* viability in the soil.	Ríos et al. (2017)
B. carinara	*P. nicoriatiae*	N/A	Pellets (DSM)	*In vitro*	Reduced chlamydospore germination.	Serrano-Pérez et al. (2017)

N/A – Not applicable. DSM – defatted seed meals.

Table 2.13

Promising experimental results obtained in the control of nematodes using biofumigation with plant species of the Brassicaceae family (Santos et al., 2021)

Biofiunigant	Taiget	Host	Stiategy	Test type	Comments	Reference
Raphanns sativus. B. júncea, Sinapis alba	Various specie»	Onion. celery	Planting and incorporation	Field	Reduced parasitic nematodes m celery	Wang et al (2006)
B carinara	*A. chitwoodi*	Potato	Pellets (DSM)	Field	Rednced nematode damage in the root and increased yield.	Henderson et al. (2009)
Various species	*Globodera pallida*	N/A	Leaf extract	*In vitro*	Presented toxicity to nematodes and inhibited the activity of juveniles.	Lord ct al. (2011)
B juncea	*A. incognita*	Tomato	Various	*In vitro*. greenhouse	Reducсd number of galls, egg mass, and eggs ni tomato plants by over 90%.	Oliveira et al. (2011)
B. carinara	*Sí. incognita*	Tomato	Liquid formulation	Bioassay	Statistically significant dose-efl'ect correlations related to isothiocyanate release.	Nicola et al. (2013)
B. júncea	*Sí.incognita*	N/A	Leaf macerates	*In vitro*	Macerate and volatile organic compCHUids released have nematicidal effect.	Barros et al. (2014)
B. júncea. R satmis, Eruca sativa	*G. pallida*	Potato	Planting and mcoiporation	Field	*B. júncea* and *R. sativus* showed to be promising for integrated nematode management systems in potatoes.	Ngala et al. (2015)
Various species	Si. *incognita*	Tomato	DSM	Greenliouse	Better results with *Eruca sativa. Barbaiva venia,* and *Brassica nigra.*	Curto et al. (2016)
R sartvus, B. júncea, S. alba	*Si. incognita*	Sweet pepper	Planting, incorporation + solarizatiou	Greenhouse	Biosolarizatiou with brassicas reducсd the population of juveniles in the soil.	Ros ct al. (2016)
R sativus. E. sativa	*M arenaria*	Tomato	Planting aud incorporation	Greenliouse	Galls aud egg masses decreased significantly.	Aydinli & Mennan (2018)
E. sativa, R sativus. B. júncea	*Sí. incognita. Sí. javanica*	Tomato, potato	Planting and uicoipoiation	Greenliouse	Reduced inoculum density and increased yield.	Daneel et al. (2018)
Crambe abyssinica	*Sí. incognita*	Tomato	Leaf extract	Greenliouse	Crambe extract weekly incorporated into the soil was promising for *Si. incognita* management in tomato.	Roncato et al (2018)

N/A – Not applicable. DSM – defatted seed meals

Table 2.14

Promising experimental results obtained in the control of phytopathogenic bacteria and protozoa using biofumigation with plant species of the Brassicaceae family (Santos et al., 2021)

Biofumigant	Target	Host	Strategy	Test t>pc	Comments	Rcfcrencc
B. oleráceo	*S. scabies*	Potato	Iucorpoiatiou of dry aud ground residues	Field	Disease suppression by 90%	Gouws and Wehner (2004)
B júnceo, R sanvus, B. oleráceo	*R. solanacearum*	Potato	Residue incorporation	Field	Significant suppression of wilt by up to 50%.	Kirkegaard (2009)
B. oleráceo	*R solanacearum.*	Ginger	Residue incorporation Must aid	Field	Lowered incidcncc of wilt and higher crop yield. Cell moitality and íuhibilion of colony Reduced seventy in roots with density greater than plants in *B. rapa* reduccd severity aud increased mass in cauliflower plants	BandyopadhyaY & Khalko (2016)
B. jtntcea	*R. solaiiaceaum* Protozoa	Tomato	essential oil	In vitro		Pontes et al. (2019)
B. rapa. B napus	*P. brassicae*	Chinese cabbage	Planting and iticotporation	Greenhouse field		Chelh et al. (2001)
B. rapo, B.napus	*P. brassicae*	Various	Planting and iucoipoiatiou	Field		Chelh et al. (2006)

N/A – Not applicable. DSM – defatted seed meals

Table 2.15

Promising experimental results obtained in the control of weeds and insects using biofumigation with plant species of the Brassicaceae family (Santos et al., 2021)

Biofuniigant	Target	Host	Strategy	Test type	Comments	Reference
B. júncea. S. alba	Weed various species	N/A	Crushed residues	*In viiro*	At the evaluated doses. *B. jmicea.* significantly inhibited weed germination.	Perniola et al. (2016)
B. júncea	Various spccics	N/A	Powder	Bioassay	Biotunugarion showed potential to be included in weed management programs. Highly effective (mortality 85% against small seeds. |0% to 20%) ngamst hard aud large seed species. Propagule mortality – 90%	Lefebyre et al. (2018)
B. Júncea	Various species	N/A	Incorporation ofcrushed residues. Powdei	Bioassav, field		Cauwer ct al. (2019)
B. júncea	Various species Insccts	NA	Crushed residues	Greenhouse	Biofiimieation with 2.5 kg m was an alternative tool for integrated weed iiuinagemeut.	Perniola el al (2019)
E. sativa	Stored product pests	N/A	ITCs extracted from seeds	Bioassay	Effects of isothiocyaiiates on adults and larv ae of stored product pests.	Shaayal Kostyukovsky (2010)
B. carinóla; B Júncea	*Agrióles bres. A sordidus. usndatus*	Lettice	DSM. chopped residues	Bioassav. field	Insecticidal eftect with high larval moHality and crop protection.	Fitilan et al. (2010)

N/A – Not applicable. DSM – defatted seed meals

It should be noted that the biofumigation activity of different parts of cruciferous plants is different. Thus, in the studies of Bellostas et al. (2007) was noted that the four species followed different patterns during growth with respect to total glucosinolate concentration (Figure 2.12). Total glucosinolate content increased from the first (leaves) to the second (buds) growth stage in *B. carinata*, *B. nigra* and *B. juncea*, with the last species being the one that showed the greatest increase. *B. nigra* and *B. juncea* subsequently showed the same pattern with a decrease in glucosinolate content at the third stage (flower) followed by a new increase towards the last stage monitored (green seeds). Total glucosinolate concentration increased in B. carinata until the flower-stage, decreasing afterwards until the green seed stage, while in B. rapa a steady decrease from the first to the last growth stage was observed.

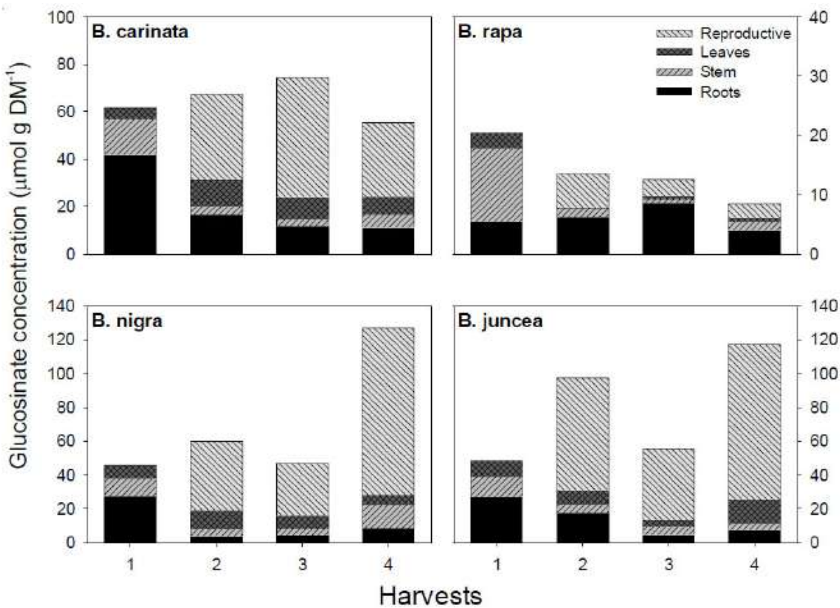

Figure 2.12 – Glucosinolate concentration (imol g DM^{-1}) in the different plant parts at the four growth stages monitored for the four species (Bellostas et al., 2007)

Glucosinolate distribution among plant parts varied with plant age and species (Figure 2.12). The roots generally showed a higher glucosinolate concentration in the first growth stage monitored (leaves) than later in the growth. Glucosinolate content of stem and leaves showed a slight decrease during the growth with total concentrations generally below 15 imol g^{-1} DM. Buds showed a large glucosinolate concentration in all species except for B. rapa, with amounts that varied from 40 to 65 imol g^{-1} DM in *B. nigra* and *B. juncea* respectively. The glucosinolate concentration in the reproductive organs decreased from this stage to the flowering stage, although values as high as 40 imol g^{-1} DM were reported in flowers of *B. juncea*. Total glucosinolate concentration increased in reproductive organs towards the end of the growth, and in the last growth stage values as high as 98 imol g^{-1} DM were found in pods of *B. nigra*.

The distribution of the different types of glucosinolates varied among plant parts during the growth cycle. Figure 2.13 shows the type of glucosinolates (aliphatic, aromatic, indol-3-ylmethyl) present in the different plant parts of the Brassica species at the last growth stage. Aliphatic glucosinolates were mainly present in the vegetative parts of the species, although they also accounted for approximately 50% of the glucosinolate content of the roots in all species, with the exception of *B. rapa* Phenethylglucosinolate was the only aromatic glucosinolate present in the species studied, being the dominant compound in the roots of B. rapa from the second growth.

The total glucosinolate production of the different plant tissues as well as of the whole plant was calculated on the basis of the glucosinolate concentration and the biomass production (Table 2.16). The maximum values were achieved at the last harvest, when both the total glucosinolate concentration in the plant and the biomass produced are at a maximum. The final glucosinolate concentration per g of soil was also estimated based on a plant density of 100 plants m^{-2}, a depth of 10 cm for incorporation of the plant material and a soil bulk density of 1.4 g cm^{-3}.

Differences in the biofumigation potential of the species studied can be expected on the basis of their glucosinolate profiles as well as of their total glucosinolate production. In general, the combination of a high glucosinolate production with the highest dry matter production towards the end of the growing period would make these stages optimal for biofumigation. However, these should not be the only factors to take into account, since many other parameters might influence the outcome of biofumigation (Figure 2.14). Incorporation of plant material into the soil plays an important role in determining a maximum glucosinolate release and different techniques for an appropriate tissue breakdown have already been investigated (Matthiessen et al., 2004). Knowledge on the cycle of the pathogen in the soil and potential side-effects towards beneficial microorganisms is also necessary other bioactive compounds present in the plant tissue, which may act independently or synergistically with glucosinolate derived products has also been suggested.

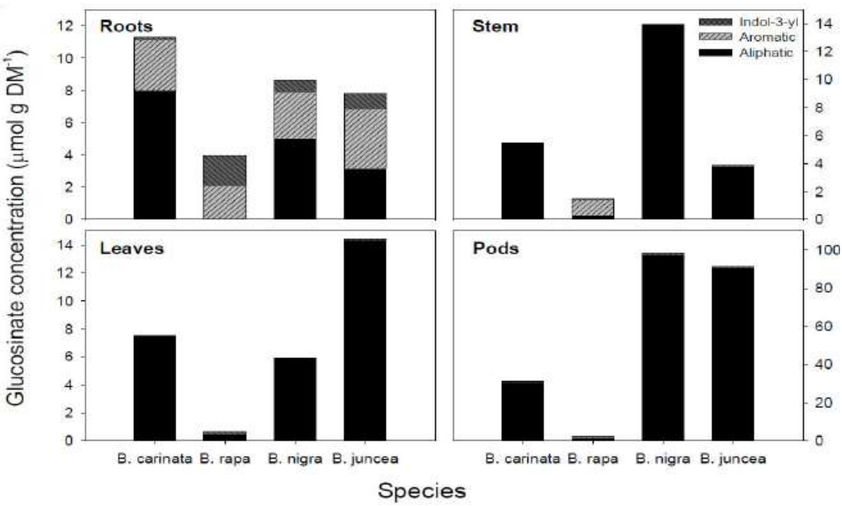

Figure 2.13 – Concentrations (imol g DM^{-1}) of different glucosinolate types (aliphatic, aromatic and indol-3-yl) present in plant parts of each species at the last growth stage monitored (green seeds in pods) (Bellostas et al., 2007)

Bellostas et al. (2007) was noted that determining the type of glucosinolates present in a certain species might be the first step for the assessment of its biofumigation potential, since transformation products resulting from glucosinolate hydrolysis have different toxicities due to their variation in structural types, physical and chemical properties. However, environmental conditions, such as pH or the presence of certain ions, influence the outcome of the myrosinase hydrolysis of a given glucosinolate. Further investigation of the different types of products resulting from myrosinase catalyzed hydrolysis of glucosinolates at different reaction conditions is therefore important in order to better define the opportunities of biofumigation as a realistic control method of soil-borne pathogens.

Table 2.16

Whole plant and tissue contribution to total glucosinolate production (imol plant^{-1} and nmol g^{-1} soil) of the four species at the four growth stages monitored (Bellostas et al., 2007)

Total glucosinolate production (nmol plant^{-1})							
Species	**Growth stage**	**Root**	**Stem**	**Leaves**	**Reproductive**	**Total**	**Total *(nmol g^{-1} soil)**
B. carinata	1	0.29	0.16	0.70	/	1.16	0.83
	2	16.62	27.64	63.46	6.01	113.73	81.23
	3	27.44	25.31	52.03	22.39	127.17	90.83
	4	49.34	188.31	35.24	243.10	516.00	368.57
B. rapa	1	0.04	0.33	0.36	/	0.73	0.52
	2	6.26	12.89	0.48	1.38	21.01	15.01
	3	5.61	3.55	1.26	1.71	12.13	8.66
	4	12.37	23.46	2.05	16.33	54.22	38.73
B. nigra	1	0.14	0.13	0.67	/	0.94	0.67
	2	5.63	40.81	56.53	26.31	129.28	92.34
	3	9.52	54.73	41.01	82.94	188.21	134.44
	4	24.06	531.66	42.48	2709.86	3308.06	2362.90
B. juncea	1	0.22	0.19	1.35	/	1.76	1.26
	2	12.96	11.40	25.25	15.46	65.06	46.47
	3	7.53	27.03	11.72	29.89	76.17	54.41
	4	12.50	44.78	53.35	1379.37	1490.00	1064.29

* Assuming 100 plants m^{-2}, 10 cm depth incorporation & soil bulk density of 1.4 g m^{-2} (Kirkegaard and Sarwar, 1998).

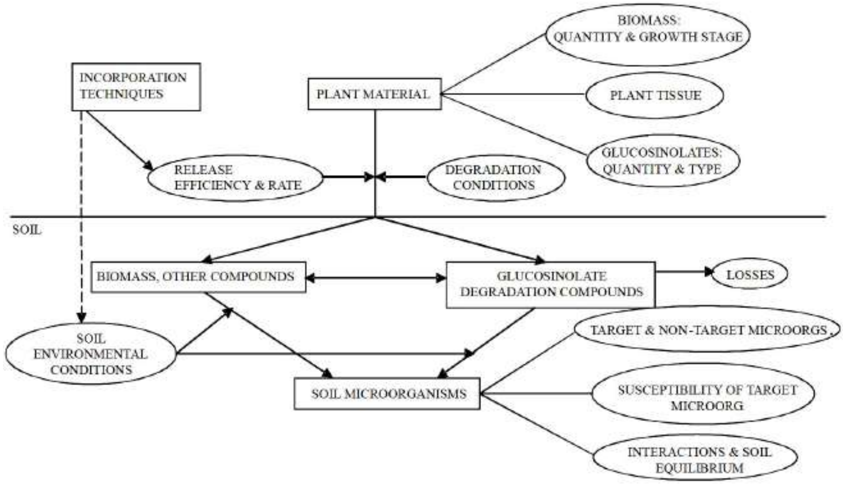

Figure 2.14 – Summary of some of the different factors influencing the outcome of biofumigation (Bellostas et al., 2007)

According to the generalizations of Clarkson et al. (2020) (in the author's original interpretation), the use of biofumigant cultures has the following aspects and expediency:

Biofumigant crops can be used in a number of different ways for disease control: Intercropping and rotations with biofumigants. In this case, above-ground plant material is harvested and hence activity against plant pathogens relies on GSLs, ITCs or other compounds released through leaf washings or root exudates. Several studies have detected both GSLs and ITCs in the rhizosphere which have been implicated in the suppression of pests and pathogens (van Dam et al., 2009) and soil organisms with myrosinase activity have been shown to mediate the conversion of GSLs to ITCs. Moreover, GSLs and ITCs can affect the composition of rhizosphere communities which may also suppress soilborne plant diseases and some common beneficial microbial species such as Trichoderma show high tolerances to ITCs (Galetti et al., 2008; Gimsing and Kirkegaard, 2009, Smith and Kirkegaard, 2002).

Incorporation of biofumigants. This is the most recognised use of biofumigant plants where a crop is grown specifically for incorporation with the aim of converting GSLs to ITCs. To achieve high levels of ITC release, comprehensive maceration of plant tissue is required followed by rapid incorporation into soil and addition of water if required to ensure complete hydrolysis (Matthiessen & Kirkegaard, 2006; Kirkegaard, 2009). As some ITCs are quite volatile, sealing/smearing the soil with a roller or covering the soil with plastic mulch may be beneficial (Kirkegaard and Matthiessen, 2004).

Seed meals and other processed biofumigants. Defatted seed meal produced after the processing of brassica seeds for oil (e.g. in mustard crops) also offer a convenient source of high GSL material for soil amendment as the myrosinase required for hydrolysis to ITCs remains intact (Brown and Mazzola, 1997). These materials have shown promise against a number of soilborne plant pathogens including Rhizoctonia spp. (Mazzola et al., 2007) and Meloidogne spp. (Lazzeri et al., 2009). A liquid formulation has also been developed from defatted B. carinata seed meal which had activity against Meloidogyne incogntta (De Nicola et al., 2012). Other products based on pellets of dried-high GSL plants have also been developed and showed good activity in vitro against Pythium and Rhizoctonia (Lazzeri et al., 2004). Simple drying of biofumigant plants can also be effective at conserving GSLs/myrosinase as reported by Michel (2014) where dried brown mustard plants (mustard hay) significantly reduced the number of Verticillium dahliae microsclerotia in a greenhouse soil. The main advantages of this approach are that these products can be used at times of year when growth of biofumigant plants is restricted (e.g. in the winter), can be more easily integrated in rotations, and are more amenable to intensive production systems where break crops are not used and there is only a short non-cropped period (e.g. protected horticulture).

Green manures and trap crops. As indicated earlier, use of biofumigant crops can have additional benefits in addition to ITC-based disease suppression such as potential (transient) increase in organic matter, better soil structure and nutrient release, all of which may increase plant vigour and growth, hence indirectly reducing the impact of soilborne plant pathogens. The use of green manures and cover crops to control soilborne diseases is the subject of another EIP-AGRI mini-paper and is not further addressed here. Some specific brassica green manures are also used as trap crops for the control of nematodes (Jaffee et al., 1998) but again this is outside the scope of this mini-paper.

According to the generalizations of Clarkson et al. (2020) with reference to Matthiessen & Kirkegaard (2006), Kirkegaard (2009) and others researchers outline very well the main ways in which biofumigation can be optimised in such ways:

1. *Establish a relationship between GSL*, ITC levels and pathogen suppression: effectively different biofumigant crops need to be screened for activity against the target pathogen. This can be done through in vitro studies particularly focussing on the effect on resting structures such chlamydospores, sclerotia and microsclerotia or ideally in soil-based assays under controlled conditions to establish the best biofumigant for a particular soilborne disease before extensive field experiments are performed. Recently an optical platform has been established that could be used as a real-time biological screen to assess effect on target pathogens post ITC application (Downie et al., 2012).

2. *Select most appropriate biofumigant or product*: in addition to considering activity against the target pathogen (1), brassica species giving rise to aliphatic short chained ITCs may be more efficient than those resulting in long chained aromatic ITCs due to increased volatility and reduced sorption of these compounds to organic matter. The biofumigant species may also need to be selected based on winter hardiness, growth rate and GSL production at different times of year depending on when it is intended to be incorporated. Seed meals and processed biofumigants may be more appropriate 1) for small, intensively cropped areas such as in greenhouses and polytunnels, and 2) for the control of more resistant resting structures such as microsclerotia of Verticillium dahiiae (Neubauer et al., 2014).

3. *Optimise agronomy*: as high amounts of biomass are required for biofumigation, agronomic factors such as seed rate, time of sowing, fertiliser application and optimal incorporation time all need to be considered in order to maximise biofumigant crop yield and GSL level. For instance, GSL concentration in plant tissue has been reported to be modified by nitrogen and sulphur supply mediated by fertilization (Li et al., 2007).

4. *Grow and incorporate high amounts of biofumigant biomass*: unpublished data from J.A Kirkegaard suggest that up to 5% w/w

fresh biomass is required to maximise pathogen suppression and typically 50 t ha-1 is required to achieve an efficacious result (Tozer Seeds, pers. comm.).

5. *Maximise incorporation efficacy and ITC release*: cell disruption is key to efficient conversion of GSLs to ITCs and equipment for pulverising and crushing plant material is superior to chopping. Immediate incorporation is then required with addition of water to maximise GSL hydrolysis and sealing the soil or tarping will maximise ITC retention.

6. *Allow 1-2 weeks before planting following crops*: ITCs and other products of GSL hydrolysis can be phytotoxic.

7. *Opinion: future directions and challenges*: since the term 'biofumigation' was first introduced just over 20 years ago there has been relatively little large scale research and commercial exploitation of the technique. However, the political and social landscape is now changing, with an increased desire from supermarkets and other end users for reduced pesticide inputs and driven also by EU legislation through the introduction of the Sustainable Use Directive and associated National IPM plans for each member state. Moreover, many of the traditional chemically-based approaches to soilborne disease control have been banned or restricted and the rate of development of new actives has declined. Hence the scene is potentially set for renewed interest and potential funding initiatives in this area.

8. *Commercial implementation*: historically, social and cultural barriers have impeded the uptake of biofumigation with the dual concerns that adoption would accelerate the removal of synthetic pesticides and the lack of trust regarding the equivalent efficacy of biofumigant crops. However, there now appears to be an increasing interest by farmers and growers in biofumigation but the variability in levels of disease control or the lack of any evidence for the benefits of this approach for particular crop-pathogen combinations are still major barriers to widespread adoption. This urgently needs to be addressed, ideally through collaborative approaches and projects between researchers and industry. There is also still a lack of consistent advice and information on some of the basic agronomy associated with growing biofumigants for maximum GSL production such as seed rate, fertiliser applications, sowing dates and biofumigant crop selection which could be further addressed by the biofumigant seed producers. In addition,

appropriate machinery optimised for maceration and incorporation is not universally accessible to growers and farmers. However, despite these barriers to implementation, there are some innovative growers who have already adopted biofumigation and integrated this technique into their farming practice. This might be in response to specific problems and it's perhaps more often the case that plant parasitic nematodes are targeted more often than soilborne fungal diseases. This may be because there is more research evidence and experience in using biofumigation for nematode control. Hence, some early adopters of the technique include potato farmers where potato cyst nematode (PCN) is a universal problem and biofumigants can be easily integrated into rotations in combination with the use of potato cultivars partially resistant to PCN.

According to the generalizations and conclusions of Clarkson et al. (2020) biofumigation has good potential for management of a range of soilborne diseases but much more evidence-based research and development is needed to implement the technique more widely in order to address the main issue of variability. It is most likely that biofumigation will be promoted on the basis of its multiple benefits to farmers in addition to potential disease control and that it will form just one part of an integrated strategy for the more intractable soilborne diseases that could include other approaches such as biological control (see EIP-AGRI biological control mini-paper). To overcome social and cultural reticence in the use of biofumigants and to promote adherence to recent EU directives on pesticide usage, an incentivisation scheme perhaps as a component of CAP reform could also be a way forward.

Tagged (Biomass Production of Biofumigant Cover Crops, 2014) a new group of cover crops for winter and summer use include mustards, oilseed radishes, and turnips. These crops belong to the family Brassicaceae, which also includes the vegetable crops radish, turnip, collards, broccoli, cauliflower, and cabbage. When young, these plants resemble turnip greens, are very succulent, and have a low C:N ratio, resulting in rapid decomposition when incorporated into the soil. However, if allowed to mature, bolt, and flower, they produce a large amount of biomass in a short period of time and become woody, resulting in slower decomposition than when killed at an immature stage (Figure 2.14.1–2.14.2).

Biofumigant cover crops, including mustards and oilseed radish, produce a group of compounds known as glucosinolates. When these Brassica cover crops are chopped with a shredder or flail mower to destroy plant cells, chemical reactions convert these glucosinolates to isothiocyanates (ITCs). ITCs are used commercially in the control of numerous crop pests including nematodes, disease-causing pathogens, and weeds. Biofumigant cover crops may offer a natural way to fumigate soil with the use of these isothiocyanates.

These potential biofumigants become especially important with the loss of methyl bromide, a fumigant used in the production of high-value vegetable and fruit crops like tomato, pepper, and strawberry. The potential fumigant properties and the physical benefits of cover cropping make Brassica cover crops valuable in cropping systems. However, little is known about the biomass production of oilseed radish and 'Caliente' mustard. Therefore, field experiments were conducted in both spring and summer to determine the biomass produced by these two Brassica cover crops at three different seeding rates.

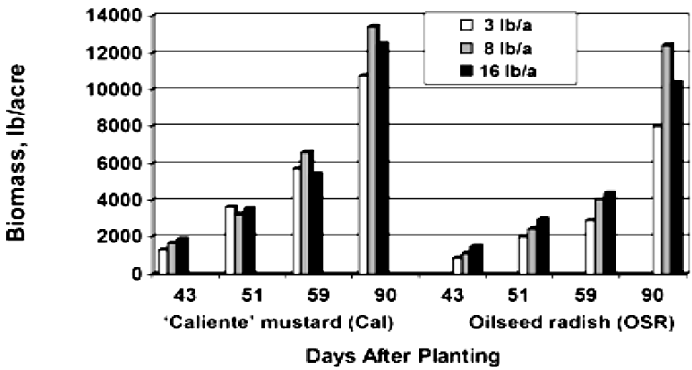

Figure 2.14.1 – 'Caliente' biomass production in spring 2007. 'Caliente' mustard and oilseed radish biomass production in spring 2007. Seeding date was March 31, seeding rate was 3, 8, 16 pounds per acre, and harvest dates correspond to 43, 51, 59, and 90 days after planting (DAP) (Biomass Production of Biofumigant Cover Crops, 2014)

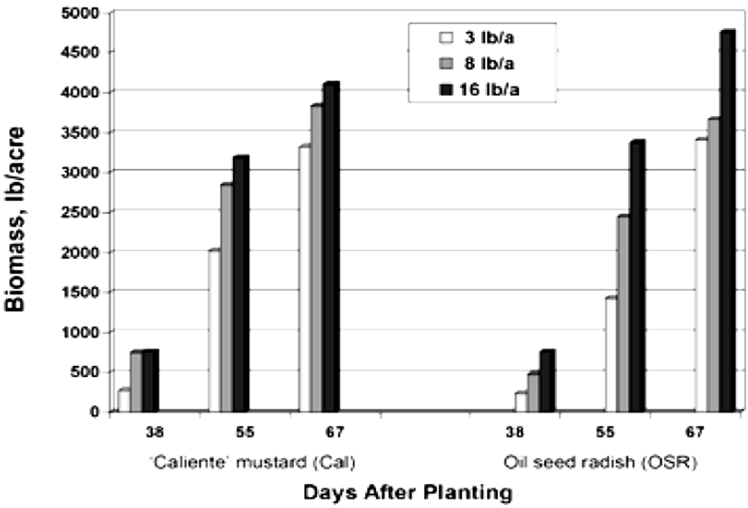

Figure 2.14.2 – 'Caliente' mustard and oilseed radish biomass production in spring 2008. Seeding date was April 1, seeding rate was 3, 8, 16 pounds per acre, and harvest dates correspond to 38, 55, and 67 days after planting (DAP) (Biomass Production of Biofumigant Cover Crops, 2014)

Like any cover crop, Brassica cover crops have limitations. Because these cover crops are closely related to important vegetable crops, (cabbage, collards, broccoli, and greens), crop rotation limitations may exist. A grower producing cabbage may not want to use a Brassica species as a cover crop for fear of disease and insect pests in the cover crop affecting the cabbage crop. However, growers producing vegetables not related to the Brassicas, such as tomato, pepper, squash, and melons, or row crops such as corn, cotton, soybeans, wheat, and tobacco, can include Brassicas in a rotation without fear of any pests moving from the cover crop to these marketable crops. Biomass production can be beneficial for the nutrients recycled, carbon added to the soil organic matter pool, and isothiocyanate produced for potential pest reductions.

2.2. Practical application of oilseed radish in soil biofumigation options

The strategy of using oilseed radish to limit the number of soil nematodes is known and widely used in production practice. Thus, in the scientific work of Mbiro (2016) it is indicated that due to a policy to increase biodiversity farmers are financially rewarded if they use mixtures of green manures. For farmers with *P. penetrans* and *M. chitwoodi* problems the options are limited and therefore research on green manure mixtures is needed. Based on this study the classical clover-ryegrass mixtures are not ideal but fodder radish (resistant cultivar) and arugula (cv. Nemat) can be successful (Table 2.17–2.18, Figure 2.15–2.18).

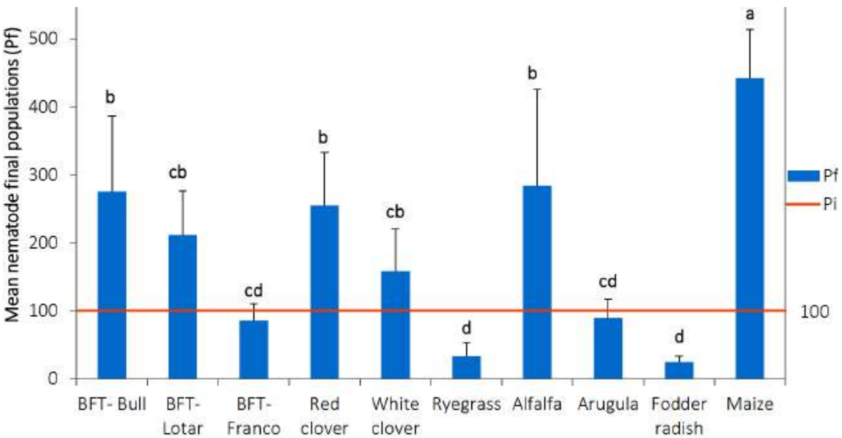

Figure 2.15 – Mean population of *P. penetrans* from a combination of organic and mineral soil fractions of different green manure plant cultivars extracted 8 weeks after inoculation with 100 (juveniles and adults) in yellow tubes. Error bars show standard error and letters indicate significantly similar and dissimilar groups (n= 6 and P < 0.05). Pf = Nematode final population, Pi = Nematode initial inoculation, BFT = Bird's-foot trefoil (Mbiro, 2016)

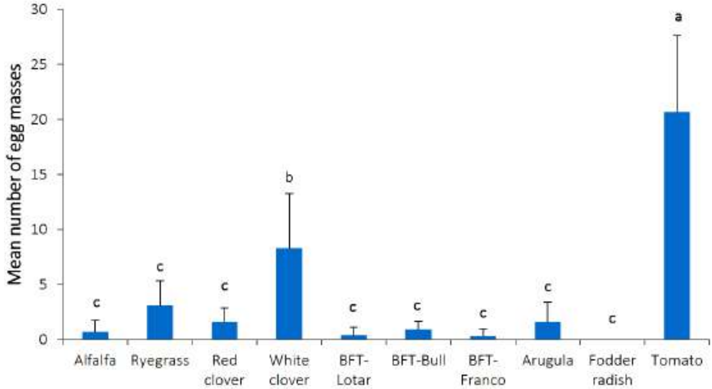

Figure 2.16 – Mean number of egg masses observed on roots of different green manure cultivars 8 weeks after inoculation with 100 second-stage juveniles of M. chitwoodi. Error bars show standard error and letters indicate significantly similar and dissimilar groups (n= 10 and *P < 0.05*), BFT = Bird's-foot trefoil (Mbiro, 2016)

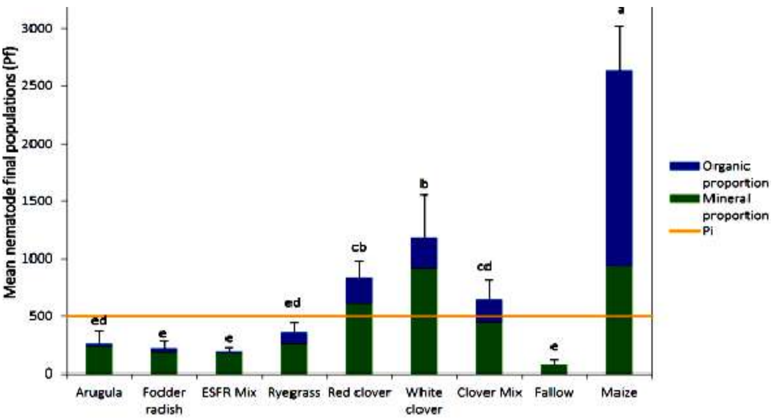

Figure 2.17 – Mean population of *P. penetrans* (organic and mineral soil fraction) of different green manure plant cultivars extracted 8 weeks after inoculation with 500 juveniles and adults. Error bars show standard error and letters indicate significantly similar and dissimilar groups (n = 5 and *P < 0.05*). Pf = Nematode final population, Pi = Nematode initial inoculation, ESFR = Arugula-fodder radish (oilseed radish) mix (Mbiro, 2016)

Putting into consideration that different geographical areas have differing soil properties and abiotic factors. It is essential first to select potential green manure plants that are adapted and best fit into the local climatical crop rotation. It is recommended to carry out greenhouse or field micro-plots for the various selected green manure plants to test for their host suitability to the target pathogens before attempting larger scale field experience through farmers. For a Belgian farmer willing to adopt organic farming, increase his or her crop yields and obtain monetary incentives from the use of green manure mixtures provided by the European Union, it should be a collaborative approach and advice from plant pathologists in different disciplines, plant breeders and geneticists as well.

Table 2.17

The number of eggs, juveniles and adults in organic and mineral fraction and their respective reproductive factor (Rf) on different green manure plant cultivars extracted 8 weeks after inoculation with 500 *P. penetrans* (mixture of juvenile and adult stages). A susceptible maize control and a fallow were subjected to the same inoculation (Mbiro, 2016)

Plants	Root weight (g)	Nematode population after 8 weeks			Rf	Host status
		Organic fraction g^{-1} fresh root	Mineral proportion 2000 g^{-1} soil	Final Populations (Pf)		
Arugula	3.65±0.27	6.0	236±116.10 [de]	258±110.97[e]	0.52	Poor
Fodder radish (Oilseed radish)	3.54±0.78	9.3	184±60.66[de]	217.2±65.52[e]	0.43	Poor
ESFR Mix	2.30±0.20	5.9	176±43.36[de]	189.6±35.65[e]	0.38	Poor
Ryegrass	14.23±1.44	7.2	256±63.88[de]	358±81.895[e]	0.72	Poor
Red clover	4.32±1.27	52.6	612±114.54[bc]	839.2±145.74[bc]	1.68	Mainte-nance
White clover	3.70±0.85	77.9	920±367.97[ab]	1177.2±375.88[b]	2.35	Good
Clover Mix	13.0±2.46	15.6	444±84.14[cd]	647.2±167.47[cd]	1.29	Mainte-nance
Fallow			76±38.47[e]	76.0±38.47[e]	0.15	
Maize	29.47±3.66	57.47	940±167.33[a]	2632.4±391.97[a]	5.26	Excellent

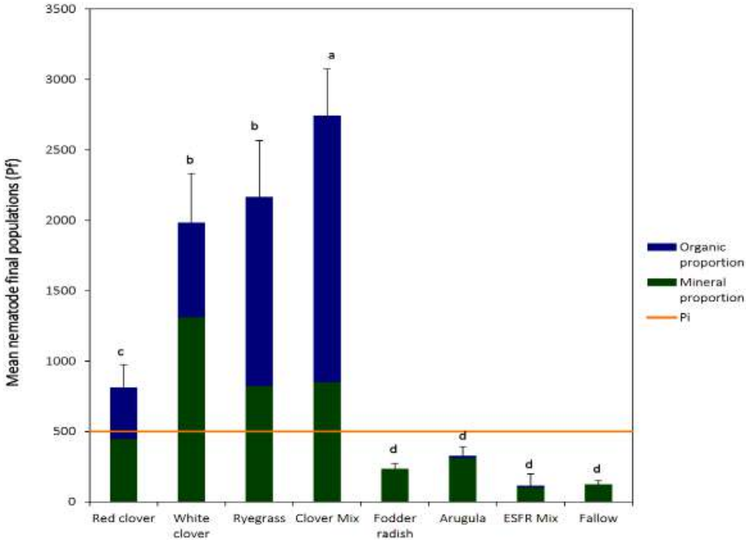

Figure 2.18 – Mean population of *M. chitwoodi* from a combination of organic and mineral soil fraction of different green manure plant cultivars extracted 8 weeks after inoculation with 500 second-stage juveniles. Error bars show standard error and letters indicate significantly similar and dissimilar groups (n = 5 and P < 0.05). Pi = initial nematode inoculation, ESFR = Arugula-fodder radish (oilseed radish) mix (Mbiro, 2016)

Table 2.18

The mean number of eggs, juveniles and adults in organic and mineral fraction and their respective reproductive factor (Rf) on different green manure plant cultivars extracted 8 weeks after inoculation with 500 second-stage juveniles of *M. chitwoodi.* A negative control (fallow) was subjected to the same inoculation (Mbiro, 2016)

Plant	Root weight (g)	Nematode population after 8 weeks			Rf	Host status
		Organic fraction g^{-1} fresh root	Mineral proportion 2000 g^{-1} soil	Final populations (Pf)		
1	2	3	4	5	6	7
Red clover	3.64±0.56	100.3	448±180.33^{c}	813.2±163.65^{c}	1.63	Main-tenance

(End of Table 2.18)

1	2	3	4	5	6	7
White clover	3.33±1.29	201.8	1312±263.29 [a]	1984±347.69[b]	3.97	Good
Ryegrass	11.09±1.76	121.1	824±12.81[b]	2167.6±396.91[b]	4.33	Good
Clover mix	11.81±1.06	160.1	852±136.09[b]	2743.2±332.22[a]	5.49	Good
Fodder radish (Oilseed radish)	3.02±0.22	0	236±38.47[cd]	236±38.47[d]	0.47	Non
Arugula	2.29±0.71	6.8	312±71.55[cd]	327.6±64.92[d]	0.65	Poor
ESFR mix	2.64±0.51	3.9	104±81.73[d]	114.4±83.51[d]	0.23	Poor
Fallow			124±26.08[d]	124±26.07[d]	0.25	

The research by Back et al. (2019) proved the effectiveness of using cruciferous plant species, including oil radish, against potato cyst nematode (PCN) (Table 2.19–2.21).

Table 2.19

Viable population densities of potato cyst nematodes (viable eggs g-1 soil) sampled from field plots with Brassica juncea, Sinapis alba, Raphanus sativus, Eruca sativa or left fallow in field experiment 2013–2014 (Samples collected pre-sowing, pre, incorporation and post-incorporation of the brassica cover crops) (Back et al., 2019)

Treatment	Viable eggs g^{-1} soil pre-sowing (August 2013)	Viable eggs g^{-1} soil pre-incorporation (November 2013)	Viable eggs g^{-1} soil post-incorporation (January 2014)	Viable eggs g^{-1} soil post-incorporation (April 2014)
Untreated	20	13	20	24
Caliente 99 *(Brassica juncea)*	11	16	18	32
Ida Gold *(Sinapis alba)*	14	16	26	28
Bento *(Raphanus sativus (oilseed radish))*	9	12	19	22
Nemat *(Eruca sativa)*	17	20	30	27
Significance (P-value)	NS	NS	NS	NS
SED	6.57	3.55	7.08	8.21
%CV	53.8	36.6	49.6	48.8

Table 2.20

The viability of potato cyst nematode eggs (%) sampled from field plots with Brassica juncea, Sinapis alba, Raphanus sativus, Eruca sativa or left fallow in field experiment 2013–2014 (Samples collected pre-sowing, pre, incorporation and post-incorporation of the brassica cover crops) (Back et al., 2019)

Treatment	% PCN eggs viable pre-sowing (August 2013)	% PCN eggs viable pre-incorporation (November 2013)	% PCN eggs viable post-incorporation (January 2014)	% PCN eggs viable post-incorporation (April 2014)
Untreated	75	67	43	43
Caliente 99 *(Brassica juncea)*	65	71	46	50
Ida Gold *(Sinapis alba)*	71	68	53	52
Bento *(Raphanus sativus)*	49	67	42	47
Nemat *(Eruca sativa)*	70	72	42	47
Significance (P-value)	NS	NS	NS	NS
SED	5.21	7.14	6.97	7.20
%CV	12.4	16.3	24.4	23.8

Table 2.21

Population densities of potato cyst nematodes (eggs g -1 soil) sampled from field plots with Brassica juncea, Sinapis alba, Raphanus sativus, Eruca sativa or left fallow in field experiment 2013–2014 (Samples collected pre-sowing, pre, incorporation and post-incorporation of the brassica cover crops) (Back et al., 2019)

Treatment	Eggs g^{-1} soil pre- sowing (August 2013)	Eggs g^{-1} soil pre-incorporation (November 2013)	Eggs g^{-1} soil post-incorporation (February 2014)	Eggs g^{-1} soil post-incorporation (April 2014)
1	2	3	4	5
Untreated	20.4	5.2	6.2	9.6
Caliente 99 *(Brassica juncea)*	13.8	4.0	7.6	11.2

(End of Table 2.21)

1	2	3	4	5
Ida Gold *(Sinapis alba)*	13.4	4.8	7.0	4.2
Bento *(Raphanus sativus)*	12.6	6.8	5.0	7.0
Nemat (Eruca sativa)	13.4	5.6	5.20	4.8
Significance (P-value)	NS	NS	NS	NS
SED	4.91	2.97	2.43	4.36
%CV	52.7	89.1	61.8	93.7

At the same time, Hansen (2011) proved the effectiveness of oil radish as a biofumigant in terms of transformation of glucosinolates in the soil (Table 2.22-2.23).

Table 2.22

Mean amount of isothiocyanate detected in soil samples after incorporation (Fall-planted brassicas) (Hansen, 2011)

Sampling Time[z] Isothiocyanate	**Pacific Gold Mustard ITCs fag g^{-1} dry soil) (data range)**	**Oilseed Radish ITCs fag g^{-1} dry soil) (data range)**	**Winter Rapeseed ITCs fag g^{-1} dry soil) (data range)**	**Weedy Fallow ITCs fag g^{-1} dry soil) (data range)**
4 hours				
Allyl	5.91 (4.36-8.58)	nd	nd	nd
Benzyl	nd*	nd	nd	0.14 (nd-0.43)
2-phenylethyl	nd	nd	nd	nd
Subtotal	5.91	nd	nd	0.14
2 Days				
Allyl	3.01 (0.65-5.89)	0.56 (0-1.67)	4.99 (0-14.96)	nd
Benzyl	nd	nd	nd	nd
2-phenylethyl	0.13 (nd-0.39)	nd	nd	nd
Subtotal	3.14	0.56	4.99	nd

[y]All values are the mean of three replicates. [z]Sampling times correspond to time elapsed after brassica incorporation. * nd = none detected above the GC-MS limit of detection (limit of detection = 0.005 picogram ITC mL^{-1}.

Table 2.23

Mean amount of isothiocyanate detected following incorporation (Spring-planted brassicas) (Hansen, 2011)

Sampling Time^z Isothiocyanate	**Pacific Gold Mustard ITCs fag g^{-1} dry soil) *(data range)***	**Oilseed Radish ITCs fag g^{-1} dry soil) *(data range)***	**Winter Rapeseed ITCs fag g^{-1} ^{dr}y soil) *(data range)***	**Weedy Fallow ITCs fag g^{-1} dry soil) *(data range)***
4 hours				
Allyl	1.58 (nd-4.86)	nd	nd	0.13 (nd-0.53)
Benzyl	nd*	nd	0.16 (nd-0.63)	0.17 (nd-0.36)
2-phenylethyl	nd	nd	0.28 (nd-l.12)	nd
Subtotal	1.58	nd	0.44	0.3
2 Days				
Allyl	0.57 (0.5-0.62)	nd	nd	nd
Benzyl	0.06 (nd-0.23)	nd	nd	0.11 (nd-0.43)
2-phenylethyl	0.15 (nd-0.32)	nd	0.44 (nd-0.88)	nd
Subtotal	0.78	nd	0.44	0.11
4 Days				
Allyl	0.22 (nd-0.89)	nd	nd	nd
Benzyl	nd	nd	nd	0.07 (nd-0.27)
2-phenylethyl	nd	nd	0.14 (nd-0.54)	nd
Subtotal	0.22	nd	0.14	0.07

^{y} All values are the mean of four replicates.

^{z} Sampling times correspond to time elapsed after brassica incorporation. * nd = none detected above the GC-MS limit of detection (limit of detection = 0.005 picograms ITC mL^{-1}.

The effectiveness of using oilseed radish in the control of Fusarium pathogens in the soil through the process of biofumigation has been proved (Table 2.24)

In addition to the positive impact of biofumigation, the impact of this process on improving the microbiological portfolio of soil was also studied (Wieczorek et al., 2024). In the review by Wieczorek et al., 2024, with references to other literature sources, it is noted that plants used for biofumigation provide the soil with a large amount of organic matter.

Table 2.24

Type and concentration of glucosinolates in freeze-dried tissue of brassicas grown in a field experiment to assess the effect of biofumigation on *Fusarium grami* nearum in a wheat-maize rotation (Ashiq et al., 2022)

Glucosinolate (nmol g^{-1}	B.juncea	'Brons'	B. carinata 'Cappucchino'		R. sativus	'Bokito'	R. sativus (oilseed radish) 'Terranova'		E. sativa 'Trio'		B. oleracea var. caulorapa L. 'Kolibri'	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Glucoberin	2.25 (0.32) [a]	2.17 (0.38)	2.01 (0.63)	1.89 (0.39)	2.33 (0.74)	2.22 (0.53)	2.35 (0.41)	2.25 (0.75)	2.06 (0.58)	2.18 (0.49)	2.24 (0.21)	1.83 (0.50)
Progoitrin	0.42 (0.13)	0.37 (0.08)	0.34 (0.23)	0.25 (0.17)	0.42 (0.31)	0.54 (0.39)	0.33 (0.22)	0.34 (0.27)	2.08 (1.49)	1.65 (1.02)	0.39 (0.27)	0.18 (0.13)
Sinigrin	26.39 (12.42)	19.97 (12.33)	13.06 (6.21)	4.81 (3.24)	-	-	-	-	-	-	-	-
Gluconapin	0.20 (0.14)	0.14 (0.17)	-	-	-	-	-	-	-	-	-	-
Glucobrassicin	0.17 (0.07)	0.32 (0.04)	0.65 (0.30)	0.43 (0.31)	1.43 (0.79)	1.54 (1.48)	2.05 (1.29)	0.78 (0.67)	0.38 (0.38)	0.05 (0.07)	1.19 (0.76)	0.91 (0.19)
Gluconasturtiin	1.32 (0.70)	18.04 (3.76)	0.42 (0.29)	6.17 (3.50)	1.12 (0.49)	2.47 (1.74)	1.28 (0.61)	2.38 (2.22)	0.90 (0.42)	2.96 (2.18)	0.52 (0.37)	5.42 (1.75)
Neogluco-brassicin	0.07 (0.03)	0.90 (0.17)	0.11 (0.07)	0.61 (0.44)	-	0.42 (0.38)	0.02 (0.03)	0.12 (0.13)	0.03 (0.02)	0.00	0.53 (0.36)	4.35 (1.82)
Glucoraphanin	-	-	-	-	7.84 (4.79)	1.39 (0.95)	5.24 (4.43)	1.47 (1.11)	7.36 (3.96)	3.94 (2.07)	3.45 (2.72)	1.30 (0.67)
Glucoraphenin	-	-	-	-	0.45 (0.11)	-	0.35 (0.19)	-	-	-	-	-
4 hydroxy glucobrassicin	-	0.04 (0.05)	-	-	-	-	-	0.02 (0.03)	-	-	-	0.27 (0.12)
Glucoraphasatin	-	-	-	-	2.43 (1.69)	14.90 (9.77)	3.45 (2.60)	17.60 (10.92)	-	-	-	-
Glucoalyssin	-	-	-	-	-	-	-	-	0.50 (0.21)	0.24 (0.21)	-	-
Glucoerucin	-	-	-	-	-	-	-	-	7.03 (3.65)	12.28 (7.30)	0.14 (0.16)	3.80 (1.71)
4-mercaptobutyl	-	-	-	-	-	-	-	-	4.89 (2.04)	1.26 (1.94)	-	-
unknown	-	-	-	-	-	-	-	-	0.53 (0.37)	-	-	-
unknown	-	-	-	-	-	-	-	-	0.93 (0.70)	-	-	-
Total glucosinolates	30.83 (13.76)	41.91 (15.63)	16.59 (7.62)	14.19 (7.31)	16.02 (8.66)	23.47 (14.65)	15.06 (7.33)	24.96 (15.10)	26.69 (12.33)	24.57 (12.69)	8.46 (4.55)	18.06 (6.22)

[a] n = 4, numbers in parentheses represent the standard error of the mean.

In consequence, there are a sufficient amount of nutrients for microorganisms, which produce more enzymes. These are the reasons for the increased enzyme activity and respiratory activity of the replanted soil in the variants with biofumigation treatment. Other researchers indicate a positive correlation between the content of organic matter in the soil and its enzyme activity (Yuan and Yue, 2012; Zhan and Sun, 2014].

The activity of soil enzymes depends on the physicochemical properties of soil (pH, organic matter content, heavy metal contamination), climate, and cultivation system (Zhan and Sun, 2014). According to Weaver (2012), an insufficient amount of water in the soil may significantly limit the enzyme activity. In our experiment, the enzyme activity and respiratory activity of the of soil were analysed in spring, summer, and autumn. There were differences in the results depending on the vegetation period.

The activity of soil enzymes because increased moisture facilitates the solution of organic matter in the soil (Geisseler et al., 2011). Sardans et al. (2005) observed that a 10% decrease in the soil moisture caused the protease activity to drop by 15-66%. The high enzyme activity and respiratory activity of soil depends on the count and diversity of microbial communities. The analysis of the count of soil microorganisms conducted in our experiment confirmed the positive effect of biofumigation treatment on this parameter. The most effective plant was French marigold *(Tagetes patula)*. The total bacterial count in the *French marigold* variant was almost two times greater than in the variant without it (Figure 2.19 A).

Hanschen and Winkelmann (2020) also observed an increase in the count of plant growth- promoting bacteria in the replanted soil after the application of *Brassica juncea* and *Sinapis alba.* The analysis of the count of oomycetes and fungi gave similar results. The total count of oomycetes and fungi in the variants with French marigold and white mustard was more than two times greater than in the replanted soil without forecrops (Figure 2.19 B). There was a slightly different result in the count of actinobacteria. The total count of these microorganisms (17.92 CFU 10^5 g^{-1} d.m.) was the highest in the oilseed radish variant *(Raphanus sativus* var. oleifera) (Figure 2.19 C).

The increase in the soil enzyme activity increased the rate of mineralisation of organic matter, and consequently, the amount of macro- and micronutrients available to plants. In our experiment, significant differences in the content of macro- and micronutrients in the soil, depending on its earlier use, were noted. The content of all macro- and micronutrients (except Mn) in the replanted soil was significantly lower than in the crop rotation soil (Table 2.25). Other researchers also observed the low content of nutrients in replanted soil (Cesarano et al., 2017; Zydlik et al., 2021). The increase in the microbial activity manifested by the higher enzyme activity and respiratory activity of the soil in the variants with forecrops of three species of biofumigants translated into an increase in the content of soil macro- and micronutrients. There was a significant increase in the content of N, P, K, Zn, Cu, and Fe in the replanted soil with the phytosanitary plants, especially in the variant with Tagetes patula. The content of minerals in the oilseed radish variant (Raphanus sativus var. oleifera) was from about 9% (Fe) to about 90% (Zn) greater than in the replanted soil (RS) without forecrops (Table 2.25).

Table 2.25

Content of macro- and microelements (mg dm ^{3}) in the soil in 2021 (CRS = crop rotation soil; RS = replanted soil) (Wieczorek et al., 2024)

Mineral Elements	CRS	RS	French Marigold	White Mustard	Oilseed Radish
			Forecrop	Forecrop	Forecrop
$N\text{-}NO_3$	98.1 ± 8.62c	83.2 ± 10.4a	91.3 ± 9.77b	132.6 ± 11.2e	124.5 ± 10.7d
P	310.3 ± 16.4c	249.2 ± 21.7a	275.0 ± 26.6b	318.5 ± 30.9d	440.0 ± 36.5e
K	247.0 ± 20.6b	190.2 ± 19.8a	256.4 ± 22.3d	251.4 ± 19.6c	290.8 ± 21.9e
Ca	117.5 ± 10.3c	101.1 ± 9.4a	105.0 ± 9.90b	128.6 ± 11.2d	127.4 ± 13.6d
Mg	15.0 ± 1.34a	16.0 ± 1.72a	19.0 ± 1.63b	16.0 ± 1.45a	19.0 ± 1.9b
Zn	7.7 ± 0.67d	4.37 ± 0.74a	6.17 ± 0.56b	7.3 ± 0.60c	8.3 ± 0.49e
Cu	2.2 ± 0,11c	1.56 ± 0.09a	1.9 ± 0.08b	2.3 ± 0.10d	2.3 ± 0.94d
Mn	50.8 ± 2.34e	28.2 ± 1.96b	20.4 ± 1.36a	41.1 ± 0.45d	40.1 ± 2.17c
Fe	106.1 ± 10.3d	96.9 ± 9.75b	79.7 ± 8.32a	111.6 ± 9.69e	107.3 ± 9.73d

Means marked with the same letters do not differ significantly at a = 0.05.

Wieczorek et al., 2024 The effect of oilseed radish in combination with other crops as a biofumigant agent on the abundance of certain species of soil nematodes was also investigated. In their experiment, eleven species of nematodes were identified in the soil (Table 2.26). In the control variant (CRS), there were four species of nematodes, mostly Ecumenicus monohystera (about 34 individuals in 100 cm^3 of soil). The population of Mesorhabditis spiculigera was much smaller. The replanted soil (RS) had the most nematodes of the Mesorhabditis spiculigera and Tylenchorhynchus dubius species (79 and 60 individuals in 100 cm^3 of soil, respectively).

In this experiment, all the three species of biofumigants effectively reduced the number of nematodes, especially in the replanted soil. The French marigold (*Tagetes patula*) was highly effective, because in the variant with it, the number of nematodes of the Pratylenhus penetrans species was reduced from about 33 individuals in 100 cm^3 of soil to zero. This species belongs to the Pratylenchidae family, which is considered one of the most important pests in orchards as well as plantations of vegetables and ornamental plants. The *Pratylenhus penetrans* feed on roots, where they cause necrotic spots, which significantly reduce the active surface of the roots. In comparison with the variant without forecrops (RS), the forecrop of French marigold reduced the population of *Tylenchorhynchus dubius* several dozen times, the populations of Prismatolaimus sp. and Geocenamus nothus – about a dozen times, and the population of Mononhoides sp. – several times (Table 2.26). It is noteworthy that the population of *Tylenchorhynchus dubius* (another internal plant parasite after *Pratylenhus penetrans* that feeds on roots) in the replanted soil was significantly reduced. Tylenchorhynchus dubius is able to survive and develop in various environmental conditions. It occurs in the root zone of over one hundred plant species. The populations of species such as Ecumenicus monohystera and Mononhoides sp. in the soil with the white mustard forecrop (Sinapis alba) were completely reduced.

The populations of *Cephalobus persegnis* and *Geocenamus nothus* were also reduced several times. There were no significant variant-dependent differences in the population of Cuticularia oxycerca. Oilseed radish was relatively the least effective in reducing the number of nematodes in the replanted soil. In the variant with the forecrop of this plant, the number of nematodes of the *Geocenamus nothus* and *Terrtocephalus terrestris* species in the soil was reduced to zero. However, the populations of *Ecumenicus monohystera* and Mononhoides sp. did not change.

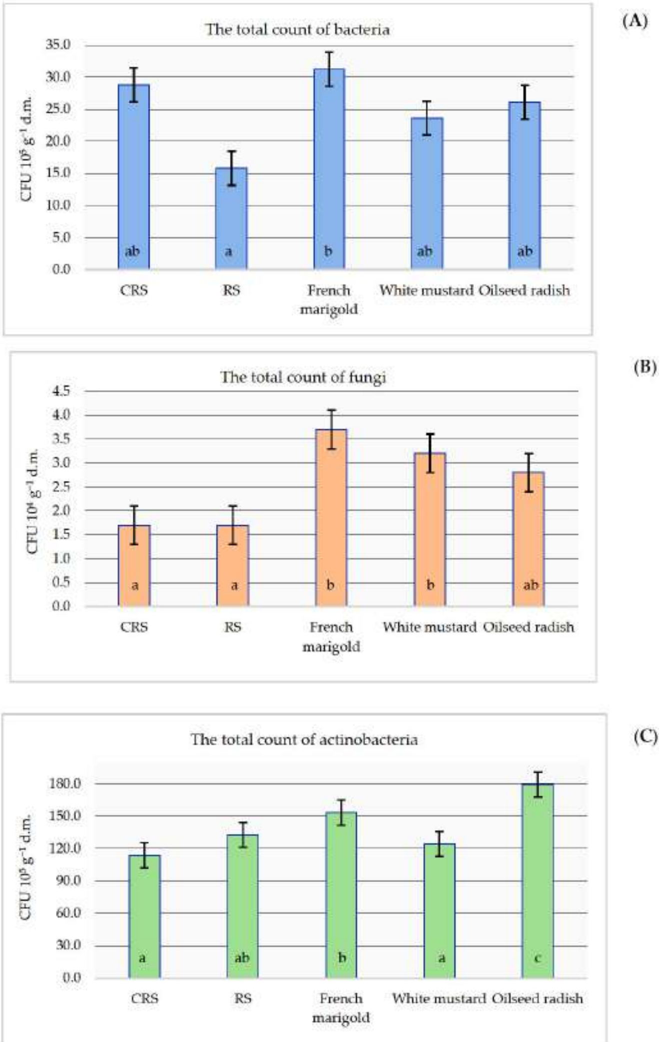

Figure 2.19 – Microbial abundance in the soil (CRS = crop rotation soil; RS = replanted soi)). Means marked with the same letters do not differ significantly at = 0.05. (Ah) The total count of bacteria; (B) The total count of fungi; (C) The total count of actinobacteria

Table 2.26

Average for years 2020–2021 nematode abundance in the soil (in 100 cm^3 of soil) (CRS = crop rotation soil; RS = replanted soil) (Wieczorek et al., 2024)

Species	CRS	RS	French Marigold Forecrop	Whight Mustard Forecrop	Oilseed Radish Forecrop
Cephalobus persegnis	4.1 ± 0.9 a	44.9 ± 9.2 b	0.0 ± 0.0 a	2.9 ± 1.0 a	1.0 ± 0.0 a
Cuticularia oxycerca	0.0 ± 0.0 a	3.3 ± 1.1 a	12.8 ± 3.4 b	3.3 ± 1.6 a	13.2 ± 3.1 a
Ecumenicus monohystera	33.9 ± 8.0 c	49.6 ± 5.6 c	44.2 ± 6.0 c	0.0 ± 0.0 a	42.7 ± 1.6 c
Geocenamus nothus	0.0 ± 0.0 a	16.5 ± 5.4 b	0.0 ± 0.0 a	0.0 ± 0.0 a	0.0 ± 0.0 a
Mesorhabditis spiculigera	19.2 ± 5.2 b	79.2 ± 8.3 c	39.5 ± 4.9 b	9.9 ± 2.2 a	75.9 ± 14.8 c
Mononhoides sp.	6.6 ± 2.0 a	13.2 ± 6.7 c	6.6 ± 1.1b	0.0 ± 0.0 a	9.9 ± 3.3 b
Panagralaimus rigidus	0.0 ± 0.0 a	56.2 ± 9.2 a	249.2 ± 24.5 b	240.9 ± 27.3 b	211.2 ± 28.1 b
Pratylenhus penetrans	0.0 ± 0.0 a	33.5 ± 5.8 c	0.2 ± 0.0 a	7.3 ± 2.0 b	7.2 ± 2.2 b
Prismatolaimus sp.	0.0 ± 0.0 a	49.5 ± 7.7 c	6.6 ± 1.0 a	19.5 ± 5.8 b	13.2 ± 3.5 a
Terrtocephalus terrestris	0.0 ± 0.0 a	21.3 ± 4.3 b	16.1 ± 3.7 b	36.0 ± 9.7 b	0.0 ± 0.0 b
Tylenchorhynchus dubius	0.0 ± 0.0 a	60.1 ± 8.8 c	3.7 ± 1.2 a	25.3 ± 4.4 b	25.1 ± 5.3 b

Means marked with the same letters do not differ significantly at a = 0.05.

The analysis of the populations (Wieczorek et al., 2024) of soil nematodes in individual years of the research showed that the nematocidal effect of the plants used for biofumigation was noticeable as early as one year after their application. The populations of eight of the eleven species of nematodes identified in 2020 decreased significantly in the following year of the research. These were mostly Geocenamus nothus, Mesorhabditis spiculigera, Mononhoides sp., Pratylenhus penetrans, and Prismatolaimus sp. In the second year of the experiment, no nematodes of these species were found in the soil more than double increase in the content of humus, as well as significant higher enzyme activity and respiratory activity in the replanted soil, in the variants with *French marigold*, white mustard, and oilseed radish was noted. Compared to the treatments without biofumi-gation, there was also a significant increase in the number of bacteria in the soil, especially in the variant with the use of *Tagetes patula*. This significantly improved the growth strength of the apple trees. The leaves of the trees in the variants with the biofumigation treatment had a larger surface area and weight (increase by 50%) than those from the trees growing on the replanted soil without forecrops. Also, the trees were taller and had a greater total growth of side shoots. The experiment also confirmed the nematocidal effect of the three species of the biofumigants, especially French marigold. The biofumigation treatment with its use made it possible to reduce the population of nematode Pratylenhus penetrans species from 33 to 0 individuals in 100 cm^{-3} of soil.

The author of the study (Wieczorek et al., 2024) concluded that biofumigation treatments using *Tagetes patula*, *Sinapis alba* and *Raphanus sativus* on replanted soil should be considered a safer and futuristic alternative to thermal disinfection and chemical fumigation, because it improves the biological properties of replanted soil and reduces the number of parasitic nematodes feeding on plants. It restores the balance of soil microorganisms and improves the growth strength of fruit trees in nurseries.

In the results of a number of zonal studies on the effectiveness of bofumigation (International Biofumigation Network, 2020; AHDB PCN, 2020; AHDB Biofumigation Report, 2022; Biofumigation For management of potato cyst nematodes (PCN), 2022) were noted that biofumigation involves incorporating brassicaceous cover crops into the soil; they produce a range of secondary metabolites in-cluding glucosinolates which can control pests. Brassicas also contain an enzyme called myrosinase. Isothiocyanates inhibit cellular respiration and other PCN functions. They can cause juvenile PCN – the young wormlike stage which invades potato roots – to hatch from their protective eggs. This causes them to starve in the absence of a host. Isothiocyanates can also paralyse or kill juveniles outright. Longer isothiocyanate exposure times and higher doses kill more PCN. Some isothiocyanates are more volatile than others, that is, they easily evaporate at normal temperatures. These isothiocyanates have lower molecular weights and are generally more mobile in soil. However, the less mobile isothiocyanates tend to be more toxic due to having more binding sites within PCN tissues. This means that trade-offs between toxicity and mobility may sometimes have to be made. The most toxic isothiocyanates to PCN in laboratory studies are allyl, 2-phenethyl and benzyl.

The glucosinolate sinigrin (2-propenyl) produces allyl, gluconasturtiin produces 2-phenethyl and glucotropaeolin produces benzyl. Few field studies have investigated biofumigant varieties that produce these isothiocyanates. Allyl is similar in toxicity and volatility to methyl-isothiocyanate, which is encouraging for PCN management. Methyl-isothiocyanate is the gas given off from metam-sodium (METAM 510®, CERTIS) and dazomet (BASAMID®, BASF). Several seed companies supply biofumigant species. Most research has been on the Indian mustard variety 'ISCI 99'. It produces high concentrations of sinigrin glucosinolate in its tissues. ISCI 99 can also produce high fresh biomass during the summer window (c.40–70 t/ha). Indian mustard and other biofumigant species are shown in Figure 2.20. Rocket and oil radish glucosinolates depend greatly on variety, whereas Indian mustards mainly contain sinigrin.

Rocket and oilseed radish varieties can produce fresh biomass of 30–40 t/ha, with oil radish having the greater biomass potential. White mustard (*Sinapis alba*) often produces high biomass. However, its main glucosinolate is glucosinalbin, which is of limited use for PCN management. Figure 2.21 shows biofumigation efficacy against PCN for published field studies. Further information, including details of seed suppliers, can be obtained from the International Biofumigation Network.

It was noted (AHDB Biofumigation Report, 2022) that a biofumigant crop needs to meet its maximum potential before being macerated and incorporated into soil for the most effective biofumigation. Biofumigation potential depends on:

– The type of glucosinolate in the crop.
– The glucosinolate concentration in crop tissues.
– The biofumigant crop biomass.

As previously mentioned, a biofumigant needs to have appropriate glucosinolates in its tissues for the pest being targeted with biofumigation. Choose a variety with a potential glucosinolate concentration in dry tissue of at least 100 |jmol g (micromoles per gram). Look for seed suppliers that state the type of glucosinolate and its concentration. A biofumigant should produce lots of biomass. Crops of 1.2-2.0 m in height usually represent in excess of 50 t/ha fresh weight, which is the goal. The more biomass produced, the more glucosinolates and the greater the potential biofumigant dose at incorporation.

Figure 2.20 – Common biofumigant species investigated for PCN management: A = *Brassica juncea* (Indian mustard), B = *Eruca sativa* (rocket), C = *Raphanus sativus* (oilseed radish) and D = *Sinapis alba* (white mustard) (AHDB PCN, 2020)

According to the results of the 2016–2017 research of Duff et al. (2021) treatments comprised nine readily available brassica biofumigants, plus three grower standards; two commonly grown cover crop varieties, Fumigator sorghum and Lablab, and a Fallow (Table 2.27). Varieties were assessed for plant biomass, days to incorporation, glucosinolate content, and efficacy against three soilborne pathogens Sclerotium rolfsii, Sclerotinia sclerotiorum and Macrophomina phaseolina. The brassica varieties trialled were flowering between 5-10 weeks when grown in summer and 9-14 weeks when grown in winter as seen in Table 2.28. The fastest-growing variety of biofumigants was BQ Mulch, taking 36 days in summer and 59 days in winter from planting to incorporation. The greatest times taken to incorporation were the varieties Nemclear and Nemcon, which actually failed to flower, even after 100+ days. Earlier work in 2016 with these varieties never saw them flowering, even after 4 months. For this reason, they were excluded from further trial work and ongoing analysis. Brassica juncea types flowered close together with Caliente maturing in 44 days when planted in summer and 98 days for it to reach flowering with a late autumn/winter planting. The two grower standard cover crops were incorporated close to 90 days after planting or when both Nemcon and Nemclear were incorporated.

Species (Common name)	Variety [supplier]	Dominant glucosinolates	Dominant isothiocayante	Recorded field efficacy (%)	Reference
Brassica juncea (Indian/brown mustard)	Caliente (ISCI) 99 [High Performance Seeds/Tozers]	sinigrin	2-propenyl/allyl	15–95	Ngala et al., 2014
		sinigrin	2-propenyl/allyl	23–37	Watts, 2018
	Variety 2 [Joordens Zaden/RAGT]	unknown	unknown	45	Watts et al., 2014
Eruca sativa (rocket/ arugula)	Nemat [High Performance Seeds/Tozers]	glucobrassicanapin	4-pentenyl	30–90	Ngala et al., 2014
	Trio [Joordens Zaden/ RAGT]	unknown	unknown	46	Watts et al., 2014
Raphanus sativus (oil radish)	Bento [P H Petersen]	glucoraphanin	(4-(methylsulfinyl) butyl/butyl	65–95	Ngala et al., 2014
		gluconsasturtiin	2-phenethyl		
Sinapis alba (white mustard)	Architect [Joordens Zaden/ RAGT]	unknown	unknown	41	Watts et al., 2014
	Zlata [Feldsaaten freudenberger]	unknown	unknown	0	Valdes et al., 2012
	Metex [P H Petersen]	unknown	unknown	16	Scholte & Vos, 2000

Figure 2.21 – Details of published biofumigation field studies focusing on potato cyst nematode management (AHDB PCN, 2020)

The research by Duff et al. (2021) also notes that up to 5 different GSLs were tested with 4 GSLs being consistently tested for over the 6 trials. Those tested for included Glucoberin, Sinigrin, Progoitrin, Gluconapin and Glucoraphanin, with the last GSL only being tested for in plants 5 and 6. Total glucosinolates, μmol/gram of dry matter, were greater during the hotter parts of the year with less during the cooler months of the year for the majority of the varieties evaluated. The levels of GSLs extracted from the different brassica biofumigants during the summer and winter growing periods or planting 1 and 4. They show that the majority of GSLs are greater during the summer than the winter planting with large differences even between varieties of brassicas grown. Figures 2.22–2.23 show how the average total GSLs for all 6 plantings changed with the time of year with most varieties producing more GSLs per gram of dry material during the warmer months of the year. Caliente and Nemfix produced the greatest amount with 53.47 µmol g_{DM}^{-1} and 52.25 µmol g_{DM}^{-1} being measured from summer grown crops respectively. BQ Mulch was the next best.

Table 2.27

Biofumigant varieties trialled 2016–2017 at the Gatton research Facility, Queensland Australia (Duff et al., 2021)

Product Name	Company	Plant Species	Rate/ha (Kg)
B.Q. Mulch®	PPG Wrightson Seeds	*25% Brassica nigra & 75% Brassica napus* (Black mustard and Fodder mustard)	10
Biofum™ Mix	Australian Premium Seeds	*Raphanus sativus & Sinapis alba* (Doublet Oilseed radish, Achilles white mustard)	10
Caliente™	E. E. Muirs and Sons	*Brassica juncea* (Indian mustard)	10
Mustclean™	Graham's Seeds	*Brassica juncea* (Indian mustard)	10
Nemat™	E. E. Muirs and Sons	*Eruca sativa* (Rocket)	8
Nemfix™	Seedmark	*Brassica juncea* (Indian mustard)	15
Nemcon™	Pature Genetics	*Brassica napus* (Fodder mustard)	10
Nemclear™	Auswestseeds	*Brassica napus* (Fodder mustard)	10
Tillage Radish®	AFG Seeds	*Raphanus sativus* (Oilseed radish)	10
Fumig8tor™ sorghum	Pacific Seeds	*Sorghum bicolor*	25
Lablab		Lablab purpureus	30

Efficacy was variable between biofumigant varieties and planting dates. Summer (Planting 1) and late winter/spring (Planting 5) exhibited better control of the various pathogens tested, particularly *S. sclerotiorum*, while autumn (Planting 3) did not exhibit the same level of effectiveness.

It is emphasized (Duff et al., 2021) that Caliente, Mustclean and Nemfix, all B. juncea, were the better varieties for controlling *S. rolfsii* in the late winter/spring planting as shown in Figure 2.25, with between 67% and 93% mortality of the buried sclerotes. Tillage Radish was the best variety for managing S. rolfsii with autumn planting with 68% mortality, as opposed to its poor performance during the summer and late winter/spring periods, where it managed only 6.7% mortality on both occasions. Caliente was the only other variety that had any significant effect on S. rolfsii when planted in autumn with 41% mortality. This was however not significantly better than the Fallow treatment which still exhibited some degree of control of S. rolfsii during summer and autumn.

Table 2.28

Days to incorporation (25% flowering) of brassica biofumigants trialled as well as grower standards (Duff et al., 2021)

	Planting date					
	15 Nov 2016	**23 Jan 2017**	**28 Mar 2017**	**16 May 2017**	**17 Jul 2017**	**20 Sept 2017**
Caliente	44	50	97	98	81	72
Mustclean	44	44	63	90	81	61
Nemfix	36	44	63	90	81	61
Nemat	70	87	69	79	67	78
Tillage Radish	70	94	97	98	67	81
Nemcon*	101	102	115	NP	NP	NP
Nemclear*	101	102	115	NP	NP	NP
Biofum	70	87	97	98	89	81
BQ Mulch	36	44	44	58	59	44
Fumig8tor sorghum	101	102	83	NP	96	88
Lablab	85	102	83	NP	NP	88

When biomass is incorporated into the equation, the amount of GSLs being produced per hectare reveals a mixed result. Some varieties producing more GSLs during winter with the greater biomass as with Caliente and Nemfix, and others still produce the least amount of GSLs during the cooler months as seen with BQ Mulch, Tillage Radish and Biofum as shown in Figure 2.24.

Sclerotinia sclerotiorum, Figure 2.25, was not managed to any great degree by any of the biofumigants with the Fallow treatment being just as effective if not better, at killing off the buried sclerotes. It wasn't until a winter/spring planting that Biofum outperformed all other treatments, including the Fallow treatment, with 50% mortality of the buried sclerotes. The autumn planting performed poorly with no significant differences between any of the treatments. This was regardless of the increased amount of plant material generated at this time of the year, Nemfix giving the greatest degree of mortality with an autumn planting at only 22% (Duff et al., 2021).

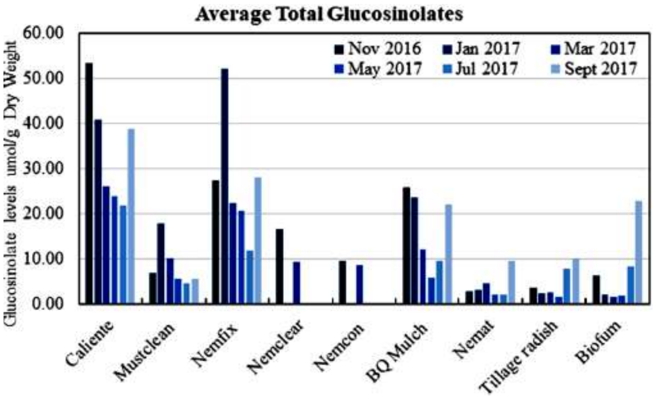

Figure 2.22 – Average total glucosinolates being produced per gram of dry material at different times of the year. performer with 25.96 µmol/g DM being produced with a summer planting also (Duff et al., 2021)

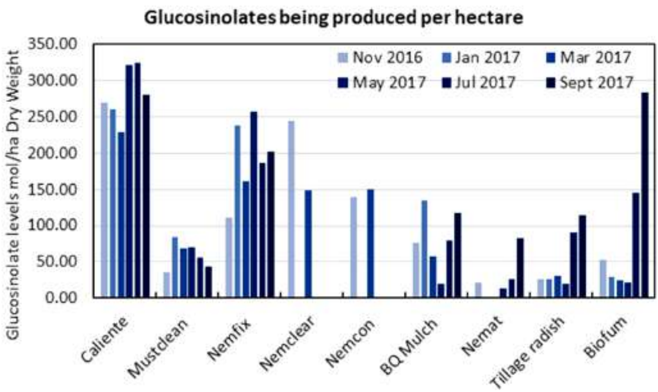

Figure 2.23 – Amount of glucosinolates being produced per hectare at different times of the year (Duff et al., 2021)

Macrophomina phaseolina (Figure 2.26) was effectively managed with Nemat and Tillage Radish during a late winter/spring planting with 93% and 100% mortality respectively of infested seed. Caliente, Mustclean and BQ Mulch were the best performers during a summer planting with

77.78%, 76.67% and 74.44% respectively. No treatment was better than the Fallow at controlling Macrophomina with an autumn planting. Bare ground Fallow treatment still managed to exert some level of control of this soilborne pathogen with 52%, 32% and 50% control being achieved during the three planting periods (Duff et al., 2021).

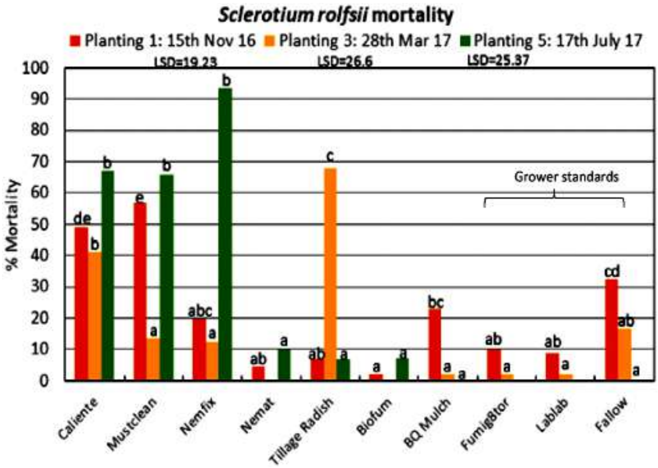

Figure 2.24 – Performance of various brassica biofumigants and grower standard practices against *Sclerotium rolfsii.* Bars with the same letter for the different plantings are not significantly different from one another (Duff et al., 2021)

The research of Wieczorek et al. (2023) proved the influence of cruciferous plant species, including oil radish, on the structure of the soil microbiological complex. The metapopulation analysis based on the analysis of the 16S rRNA sequence showed that the previous use of the soil in the nursery, the phytosanitary plants used in the experiment, and the years of research influenced the number of operational taxonomic units of bacteria in the soil (Table 2.29). Next-generation sequencing is an increasingly popular and extremely sensitive method of determining similarities and differences within the soil microbiome. This fact was confirmed by the results of our research (Table 2.30–2.32, Figures 2.27–2.29) Depending on the soil site and the year of the research, there were 20–34 bacterial phyla and 378–554 genera identified. Due to the large number of operational taxonomic units (OTUs), only those with an average share of more than 1% were shown in Figures 2.27–2.29. Throughout the study period, the following bacterial phyla were dominant in the soil: Proteobacteria (the relative abundance ranged from 33.23% to 60.08%), *Firmicutes, Actinobacteriota, Acidobacteriota, Chloroflexi,* and *Verrucomicrobiota* (Figures 2.27–2.29). Depending on the year of the soil metagenomic analyses, the following phyla were also dominant: *Bacteroidetes, Planctomycetes, Tenericutes, Spirochaetes, Chlamydiae, Cyanobacteria, Gemmati- monadota, Bacteroidota,* and *Fatescibacteria* (Figures 2.27–2.29). Experiment (Wieczorek et al., 2023) showed that, regardless of the year of the study, the most intensive proliferation of Proteobacteria was observed in the soil in variant R3, slightly weaker – in the replanted soil with the white mustard forecrop *(Sinapis alba)* (R4), and then in variant R5 (Figures 2.27–2.29). The lowest percentage of the OTU content was found in the replanted soil (R2) in 2020. A year earlier, despite several attempts to isolate the bacterial DNA, it was impossible to obtain research material due to the degree of soil sterilisation.

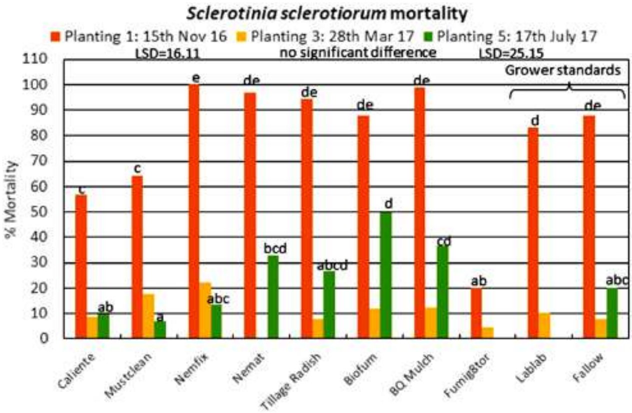

Figure 2.25 – Performance of various brassica bio fumigants and grower standard practices against *Sclerotinia sclerotiorum.* Bars with the same letter for the different plantings are not significantly different from one another. Planting 3 there was no significant difference between varieties (Duff et al., 2021)

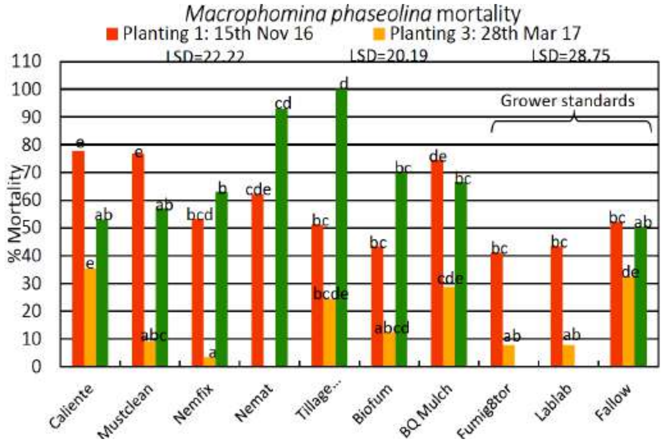

Figure 2.26 – Performance of various brassica biofumigants and grower standard practices against *Macrophomina phaseolina.* Bars with the same letter for the different plantings are not significantly different from one another (Duff et al., 2021)

Table 2.29

Number of bacterial taxonomic units according to experimental combinations (R1-agricultural soil; R2-replanted soil; R3-replanted soil with *Tagetes patula* L. foregut; R4-replanted soil with *Sinapis alba* foregut; R5-replanted soil with *Raphanus sativus* var. *oleífera* foregut) (Wieczorek et al., 2023)

Taxonomy units	R1	R2	R3	R4	Rn
1	2	3	4	5	6
2019 year					
Phylum	2o	-	22	23	23
Class	44	-	48	50	47
Order	87	-	96	93!	96
Family	180	-	201	I17	205
Genus	378	-	441	407	570
Species	456	-	591	532	704
2020 year					
Phylum	30	32	331	32	331
Class	84	89	89	90	85
Order	190	201	216	224	207
Family	280	294	320	338	317

(End of Table 2.29)

1	2	3	4	5	6
Genus	457	499	554	510	513
Species	832	906	1 00h	935	940
2021 year					
Phylum	32	30	30	33	30
Class	80	76	69	85	79
Order	180	170	105	200	189
Famüy	272	255	302	301	280
Genus	48e	458	552	553	505
Species	838	774	953	942	988

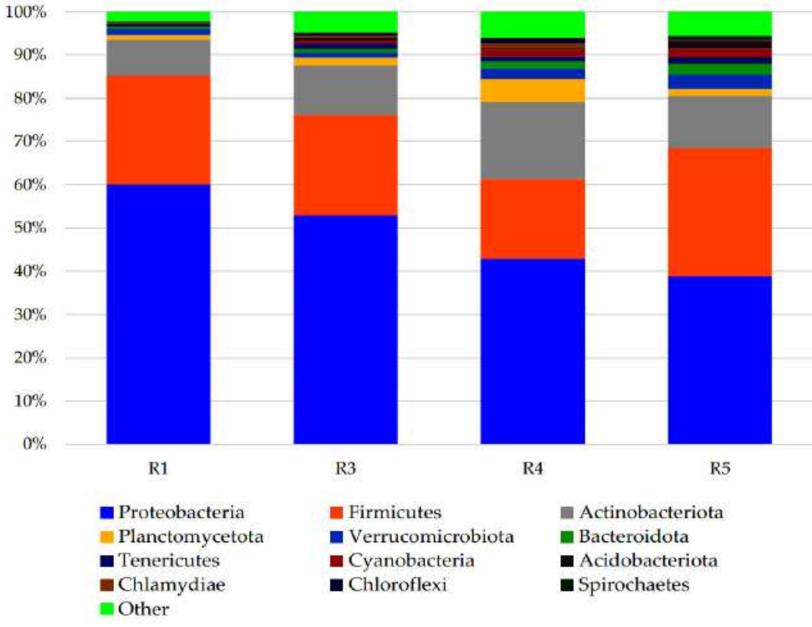

Figure 2.27 – Relative abundance o° dominant phyla o° bacteria in 2019. The classifications with less than 1% abundance are gathered into the category «Other» (R1–agricultural soil; R2–replanted soil; R3–replanted soil with *Tagetes patula* L. foregut; R4–replanted soil with *Sinapis alba* foregut; R5–replanted soil with *Raphanus sativus* var. *oleifera* foregut) (Wieczorek et al., 2023)

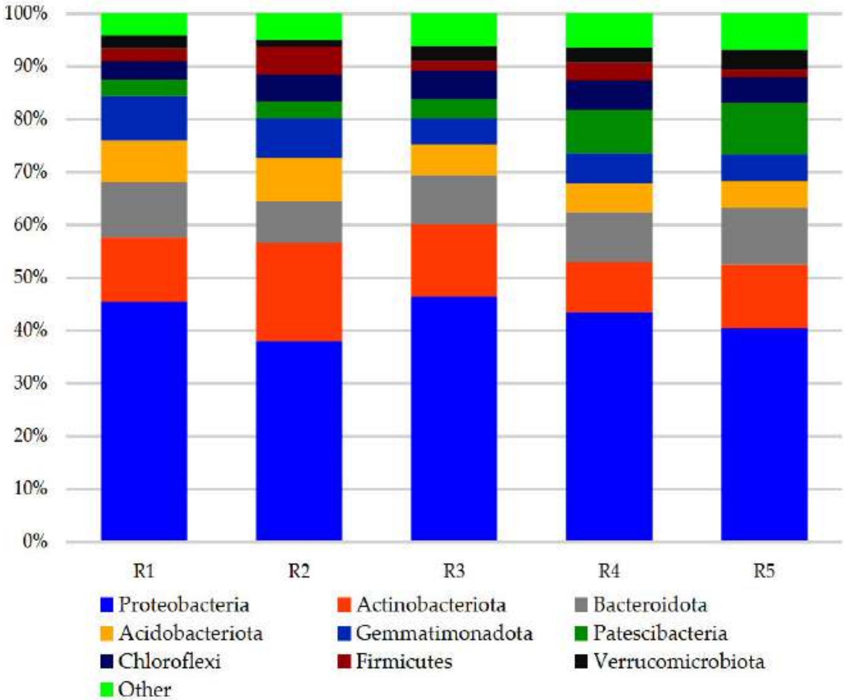

Figure 2.28 – Relative abundance of dominant phyla of bacteria in 22020. The classifications with less than 1% abundance are gathered into the category «other» (R1–agricultural soili R2–replanted soil; R3–replanted soil with *Tagetes patula* L. foregut; R4–replanted soil with *Sinapis alba* foregut; R5–replanted soil with *Raphanus sativus* -var. *oleifera f*oregut) (Wieczorek et al., 2023)

In 2019, regardless of the experimental variant, Firmicutes bacteria were the most dominant phylum (Figure 2.27). In the following years of the research, the count of Actinobacteriota increased and was greater than the counts of other bacterial phyla (Figures 2.28–2.29). The intensive growth and development of Actinobacteriota were particularly noticeable in variant R2. Actinobacteriota are a saprophytic group of actinobacteria that quickly adapt to unfavourable environmental conditions, such as desiccation.

Therefore, they actively decompose organic matter when the soil moisture is low (Wieczorek et al., 2023).

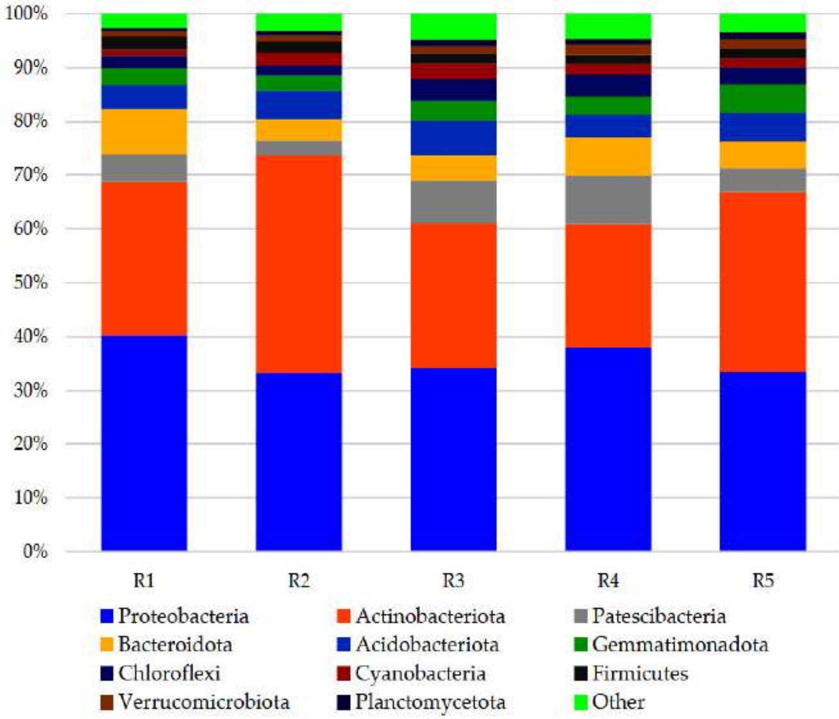

Figure 2.29 – Relative abundance of dominant phyla oo bacteria in 2021. The classifications wiih less than 1%o abundance are gathered into the category «other» (R1-agricultural soili R2-replanted soii; R3-replanted soil with *Tagetes patula* L. foregut; R4-replanted soil with *Sinapis alba* foregut; R5–replanted soil with *Raphanus sativus* var *oleifera* foregut) (Wieczorek et al., 2023)

According to the same estimates by Wieczorek et al. (2023) Figures 2.27–2.29 show relative differences between the dominant types of bacteria in the control variant (R1) and the other experimental variants, expressed as a percentage of sequence. The analysis of the research results showed that regardless of the year of the study, the OTU content of the Proteobacteria phylum in all experimental variants was lower than in the control variant (R1). However, it is necessary to stress the fact that the difference in the content of OTUs of the Proteobacteria phylum in the soils subjected to induced biofumigation with the phytosanitary plants – Tagetes patula L. (R3), Sinapis alba (R4), and Raphanus sativus var. oleífera (R5) – in relation to the agricultural soil was significantly lower than the difference observed in the soil with ARD (Figures 2.30–2.32). Apart from that, in 2020, the application of French marigold (R3–R1) caused a significant increase in the content in OTUs of the Proteobacteria phylum (Figure 2.31). Thus, it can be concluded that the application of phytosanitary plants to the soil with ARD causes an increase in the content of OTUs belonging to the Proteobacteria phylum.

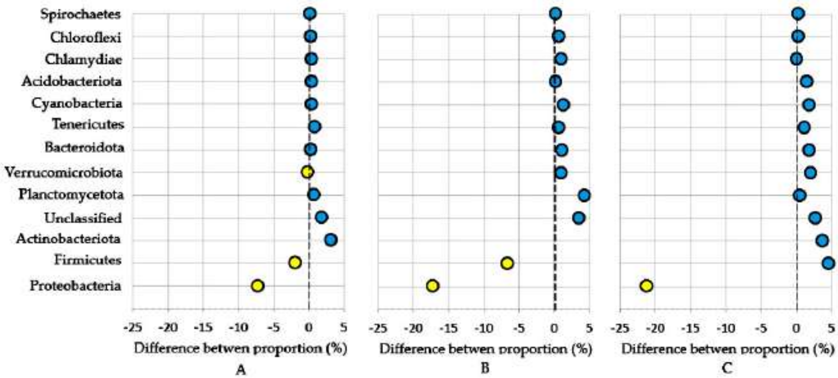

Figure 2.30 – Relative abundance of dominant classes of bacteria phyla in 2019 (A-R3 via R1; B-R4 via R1; C-R5 via R1). The classifications with less than 1% abundance are gathered into the category «other» (R1-agricultural so il; R3-replanted soil with *Tagetes patula* L. foregut; R4-replanted soil with *Sinapis alba* foragut; R5-replanted soil with *Raphanus sativus* var. *oleifera* foregut; «yellow» means negative difference; «blue» means positive difference) (Wieczorek et al., 2023)

A similar trend was also observed for the Firmicutes phylum. The metagenomic analysis of the soil conducted between 2019 and 2021 showed that the sequence content of seven bacterial phyla in the soil samples was lower than in the control variant. However, these differences were not observed in all experimental variants. They were ranked as follows according to the frequency of their occurrence in the soil: Bacteroidota > Acidobacteriota > Actinobacteriota = Gemmatimonadota > Patescibacteria.

The Verrucomicrobiota and Chloroflexi bacterial phyla, and especially Planctomycetota and Cyanobacteria, were isolated less often from the agricultural soil (R1), especially when compared with the replanted soil subjected to fumigation. The Chloroflexi phylum encompasses nitrifying bacteria developing in anaerobic or microaerophilic conditions. They can survive in intensively changing, extreme conditions. The incidence of the Chloroflexi phylum in soils with ARD after biofumigation was higher than in the control soil. This phenomenon can be explained by the fact that the development of the; community of these bacteria is based on the use of cellular compounds from dead microorganisms and their metabolites

In this study (Wieczorek et al., 2023), fumigation induced by the use of French marigold (R3) increased the content of OTUs in 2he Cyanobacteria phylum by 83% as compared with the soil with ARD and the agricultural soil. A similar trend was also observed for the Firmicutes phylum. The metagenomic analysis of the soil conducted between 2019 and 2021 showed that the sequence content of seven bacterial phyla in the soil samples was lower than in the control variant. However, these differences were not observed in all experimental variants. They were ranked as follows according to the frequency of their occurrence in the soil: Bacteroidota > Acidobacteriota > Actinobacteriota = Gemmatimonadota > Patescibacteria.

The Verrucomicrobiota and *Chloroflexi bacterial phyla*, and especially Planctomycetota and Cyanobacteria, were isolated less often from the agricultural soil (R1), especially when compared with the replanted soil subjected to fumigation. The *Chloroflexi phylum* encompasses nitrifying bacteria developing in anaerobic or microaerophilic conditions. They can survive in intensively changing, extreme conditions. The incidence of the *Chloroflexi phylum* in soils with ARD after biofumigation was higher than in the control soil. This phenomenon can be explained by the fact that the development of the; community of these bacteria is based on the use of cellular compounds from dead microorganisms and their metabolites, which is typical of soils with ARD i60] (Wieczorek et al., 2023).

In this study (Wieczorek et al., 2023), fumigation induced by the use of *French marigold* (R3) increased the content of OTUs in 2he *Cyanobacteria phylum* by 83% as compared with the soil with ARD and the agricultural soil.

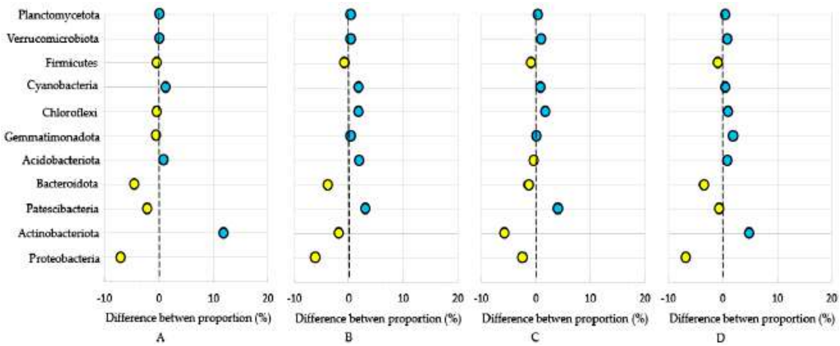

Figure 2.31 – Relative abundance of dominant classes of bacteria phyla in 2020 (A–R3 via R1; B–R4 via R1; C–R5 via R1). The classifications with less than 1% abundance are gathered into the category «other» (R1–agricultural so il; R3–replanted soil with *Tagetes patula* L. foregut; R4–re planted soil with *Sinapis alba* foragut; R5–replanted soil with *Raphanus sativus* var. *oleifera* foregut; «yellow» means negative difference; «blue» means positive difference) (Wieczorek et al., 2023)

The principal component analysis (PCA) revealed the relationships between the different types of soil bacteria in the experimental variants during the three years of the research (Figure 8). It showed that soil biodiversity ranged from 71.19% to 94.28%. It also showed that the relationships between the different types of bacteria were related to the year of the study (Wieczorek et al., 2023). Regardless of the! experimental variant, in the first year of the study, the analysis revealed a clear correlation between the percentage of taxonomic sequences oe the Verrucomicrobiota, Bacteroidota, Cyanoeactetia, and Ttnericutes phyla and between Actinobacteriota and Planctomycetota.

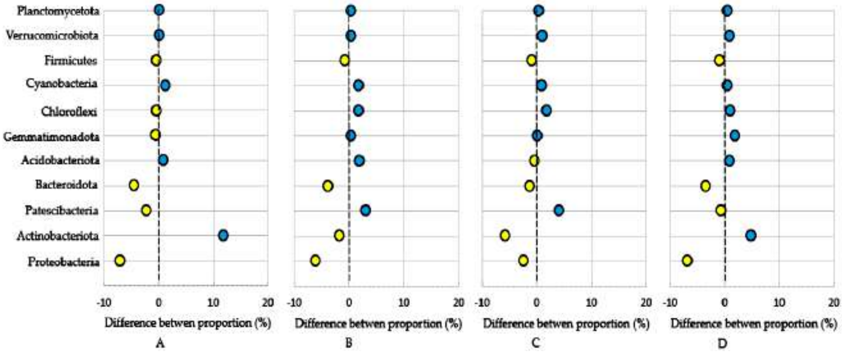

Figure 2.32 – Relative abundance of dominant classes of bacteria phyla in 2021 (A–R3 via R1; B–R4 via R1; C–R5 via R1). The classifications with less than 1% abundance are gathered into the category «other» (R1–agricultural so il; R3–replanted soil with *Tagetes patula* L. foregut; R4–re planted soil with *Sinapis alba* foragut; R5–replanted soil with *Raphanus sativus* var. *oleifera* foregut; «yellow» means negative difference; «blue» means positive difference) (Wieczorek et al., 2023)

A similar relationship between Verrucomicrobiota and Batterosdota was also observed in the second year of the study (Wieczorek et al., 2023) (Figure 2.33). However, in 2020 and 20221, there was a correlation between the percentage of OTUs in the Proteobacteria phylum and Bacteroidota.

As a result, the author of the study (Wieczorek et al., 2023) concluded that the use of metagenomics (functional analysis of genetic material isolated from the soil) as a tool for assessing soil biodiversity in the nursery after replantation proved to be a sensitive and precise method of assessment of the soil microbiome in the nursery. The analyses of the microbiome composition showed that biofumigation with phytosanitary plants – French marigold (*Tagetes patula* L.), white mustard (*Sinapis alba*), and oilseed radish (*Raphanus sativus* var. *oleifera*) – changed the structure and count of bacteria in the replanted soil in the fruit tree nursery. The phytosanitary plants increased the abundance of operational taxonomic units (OTU) of the Proteobacteria, Bacteroidota, Patescibacteria, Chloroflexi, Fatescibacteria, and Verrucomicrobiota phyla, but decreased the abundance of the Firmicutes, Acidobacteriota, and Actinobacteriota phyla. The biofumigation also increased the content of some dominant bacterial genera in the replanted soil, such as Flavobacterium, Massila, Sphingomonas, Arenimonas, and Devosia. These genera are considered crucial in promoting plant growth and inducing plant systemic immunity, which may indicate the regeneration of replanted soil.

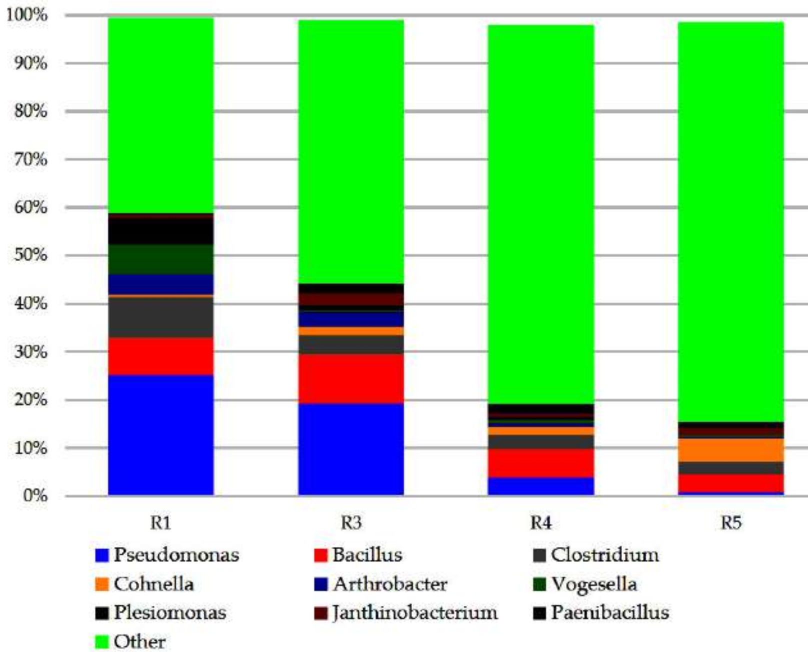

Figure 2.33 – Relative abundance of the dominant (rodzaj) genus of bacteria in 2019. The classifications with less than 1 % abundance are gathered into the category «other» (R1–agricultural soil; R2– replanted soil; R3–replanted soil with *Tagetes patula* L. foregut; R4–replanted soil with *Sinapis alba* foregut; R5–replanted soil with *Raphanus sativus* var. *oleífera* foregut) (Wieczorek et al., 2023)

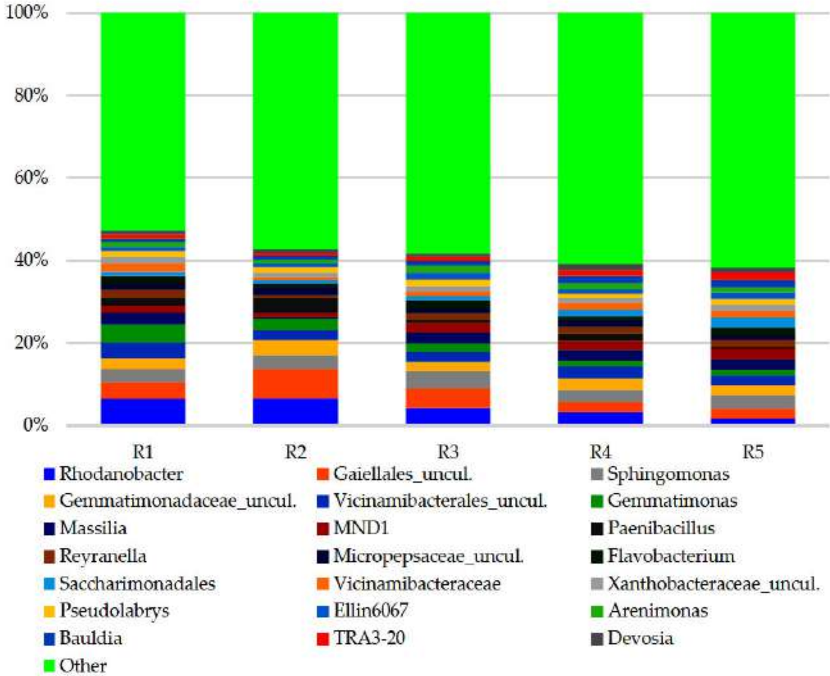

Figure 2.34 – Relative abundance of the dominant (rodzaj) genus of bacteria in 2020. The classifications with less than 1 % abundance are gathered into the category «other» (R1–agricultural soil; R2– replanted soil; R3–replanted soil with *Tagetes patula* L. foregut; R4–replanted soil with *Sinapis alba* foregut; R5–replanted soil with *Raphanus sativus* var. *oleífera* foregut) (Wieczorek et al., 2023)

Studies (Wieczorek et al., 2023) have shown that regardless of the species of phytosanitary plants used, there was an increase in the abundance of beneficial microbiomes. In practice, when planning production plantings, it is recommended to use a one-year break during which phytosanitary plants will be cultivated.

In the similar study (Nallanchakravarthula et al., 2021), strawberry yield was shown to be negatively affected by the application of oilseed radish

18 days before planting. In the experimental plots were sown on the day of incorporation, resulting in negative effects of the treatments on both stand establishment and yield in most crops.

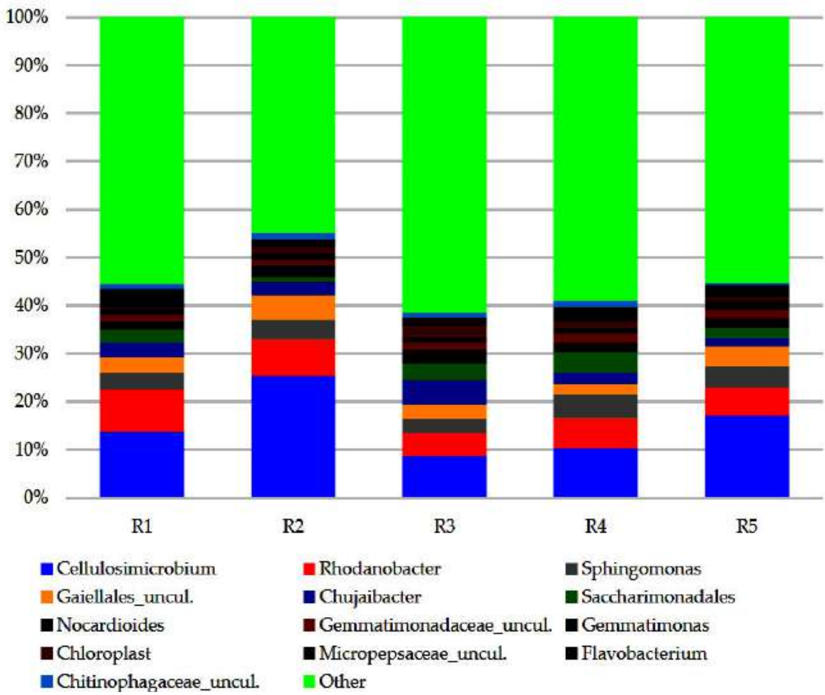

Figure 2.35 – Relative abundance of the dominant (rodzaj) genus of bacteria in 2021. The classifications with less than 1 % abundance are gathered into the category «other» (R1–agricultural soil; R2– replanted soil; R3–replanted soil with *Tagetes patula* L. foregut; R4–replanted soil with *Sinapis alba* foregut; R5–replanted soil with *Raphanus sativus* var. *oleífera* foregut) (Wieczorek et al., 2023)

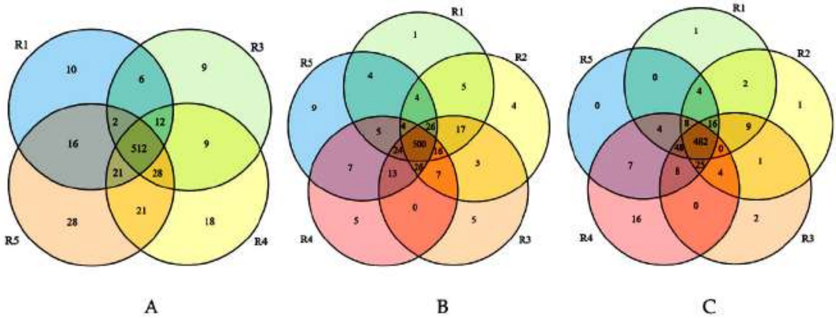

Figure 2.36 – Venn diagram of overlapping bacterial communities (phyla) (A–2019; B–2020; C–2021). (R1-agricultural soil; R2-replanted soil; 153-replanted soil with *Tagetes patula* L. foregut; R4-replanted soil with *Sinapis alba* foregut; R5-replanted soil with *Raphanus sativus* var. *oleífera* foregut.); the numbers indicate the number of unique bacterial sequences (Wieczorek et al., 2023)

However, if addition of biofumigant residues had any green manuring or nutritional effect then there should have been a significant increase in the abundance of the fungal ‘saprotrophic guild’ in rhizosphere soil (Figures 2.37–2.38) but we did not observe any major changes in abundance of dominant saprotrophs, suggesting that there was little or no green manuring effect. We therefore believe the observed effects of oilseed radish residues were more likely to be due to the ITCs and phytotoxic chemicals released after mulching of the biofumigant, although these chemicals were not measured directly in this study. In roots, the saprotrophic guild increased significantly in the +B+V treatment, with concurrent decrease in endophyte and arbuscular mycorrhizal guilds, possibly due to chemicals released from the biofumigant.

Oilseed radish incorporation was shown to change the composition of the glomeromycotan community, causing a significant decrease in the relative abundance of a taxon in the Glomeraceae. *V. dahliae*, there was a significant increase in relative enrichment of *Periconia macrospinosa* and *Microdochium bolleyi* (‘dark septate endophytes’/DSE) and an unclassified taxon belonging to Pleosporales (presumably a root endophyte) compared to corresponding control treatment without *V. dahliae* (B–V).

This response of the root endophytes could have been a result of the presence of the pathogen, and this re-structuring of the root microbiome might enable the plant to tolerate deleterious effects of the pathogen.

In conclusion (Nallanchakravarthula et al., 2021), this study provides new data suggesting that biofumigation of strawberry plants by incorporation of *Raphanus sativus* var. *oleifera* has significant effects on the composition of root fungal communities and may decrease the relative abundance of arbuscular mycorrhizal fungi and some potentially beneficial root endophytic taxa.

Table 2.30

Unique bacterial taxa in individual experimental variants in 2019. (R1-agricultural soil; R2-replanted soil; R3-replanted soil with *Tagetss patula* L. foregut; R4-replanted loil with *Sinapis alba* foregut; R5-replanted soil with *Raphanus sativus* var. *oleífera* foregut) (Wieczorek et al., 2023)

R1	R2	R3	R4	R5
Number of Unique Taxa				
10	**0**	**9**	**18**	**28**
Amicrococcus *Dorea* *Eggerthella* *Enhydrobacter* *Fructobacillus* *Mitsuokella* *Paraprevotella* *Sarcina* *Thiocystis* *Vermineplirobacter*	–	*Chlamydia* *Desulfonatro-* *novibrio* *Desulfotalea* *Flectobacillus* *Helcococcus* *Muricatida* *Roseateles* *Sinomonas* *Spirochaeta*	*Citricoccus* *Cryobacterium* *Dehalobacterium* *Desulfomicrobium* *Entomoplasma* *Fusobacterium* *Jeotgalicoccus* *Kibdelosporangium* *Kytococcus* *Octadecabacter* *Odoribacter* *Peptostreptococcuss* *Roseococcus* *Saccharomonospora* *Salinivibrio* *Sporanaerobacter* *Thermococcus* *Xenococcus*	*Antarctobacter* *Aureispira Bulleidia* *Butyricimonas* *Coprococcus* *Haliscome-nobacter* *Lachnobacterium* *Limnothrix* *Luteococcus Nevskia* *Parabacteroides* *Porphyromonas* *Propionigenium* *Pseudanabaena* *Psychroflexus* *Rhodothalassium* *Roseburia Roseiflexus* *Roseivivax* *Salinimicrobium* *Snowella* *St reptomonospora* *Sulfuricurvum* *Sulfuritalea* *Teredinibacter* *Terriglolms* *Thermacetogenium* *Zobellia*

Table 2.31

Unique bacterial taxa in individual experimental variants in 2020. (R1-agricultural soil; R2-replanted soil; R3-replanted soil with *Tagetss patula* L. foregut; R4-replanted loil with *Sinapis alba* foregut; R5-replanted soil with *Raphanus sativus* var. *oleífera* foregut) (Wieczorek et al., 2023)

R1	R2	R3	R4	R5
Number of Unique Taxa				
1	**4**	**5**	**4**	**3**
Amycolatopsis	*Haliscomenobacter* *Novibacillus* *f_Enterobacte-riaceae;* Other *Hafnia-Obesumbac-terium*	*f_Nostocaceae;* Other *Archangium* *Aetherobacter* f_Polyangiaceae; g_ uncultured *Leptospira*	*Vicingus* *Blastopirellula* *Chitinimona* *f_Parachlamy-diaceae;* g_uncultured	o_Babeliales; Other; Lactococcus 0M60(N0R5)_ clade

Table 2.32

Unique bacterial taxa in individual experimental variants in 2020. (R1-agricultural soil; R2-replanted soil; R3-replanted soil with *Tagetss patula* L. foregut; R4–replanted loil with *Sinapis alba* foregut; R5-replanted soil with *Raphanus sativus* var. *oleífera* foregut) (Wieczorek et al., 2023)

R1	R2	R3	R4	R5
Number of Unique Taxa				
1	**1**	**2**	**16**	**0**
Amycolatopsis	Rahnella1	f_Myxococcaceae; Other Candidatus_ Falkowbacteria	Paludibacter WCHB1-32 Vitellibacter Bacteriovorax Pseudarcobacter Candidatus_ Megaira Tolumonas Idiomarina Shewanella Noviherbaspirillum Candidatus_Accumulibacter f_Methylococcaceae;g_uncultured Methylophaga Halomonas Alkanindiges f_ Criblamydiaceae;g_uncultured	–

Further investigations should reveal whether negative effects of biofumigation on strawberry yield and root fungal microbiome are host genotype- or soil-dependent.

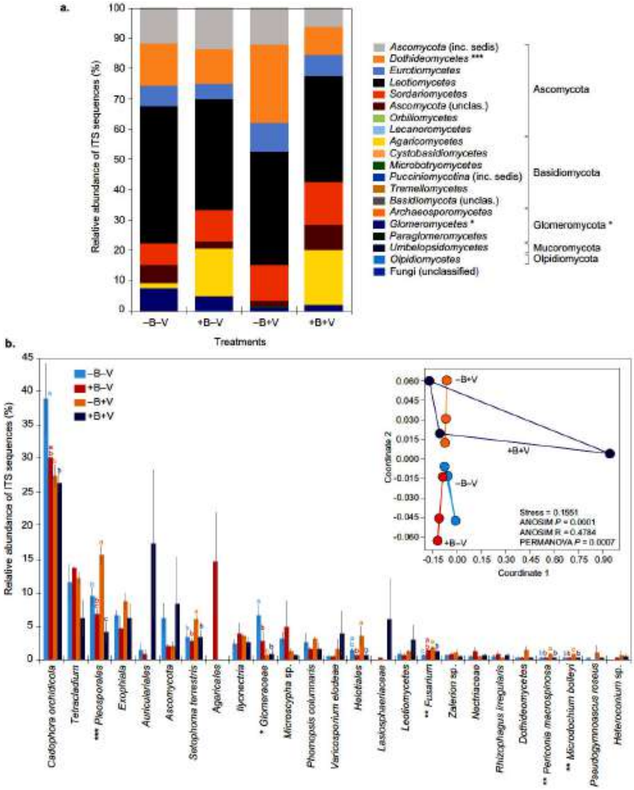

Figure 2.37 – Relative abundance of ITS sequences of different fungal classes in the roots of strawberry plants treated with factorial combinations of oilseed radish (*Raphanus sativus oleifera*) residues as biofumigant, (+/- B) and inoculation with the fungal pathogen *Verticillium dahliae* (+/- V) (a). Names of fungal phyla are given to the right of brackets grouping classes. The histogram depicts the twenty-five most abundant fungal taxa (that comprise around 95% of the ITS sequences from roots) found in all treatments, whereas the nonmetric multidimensional scaling (NMDS) ordination plot (inset) is based on all taxa (b). Analysis of variance (ANOVA) significance levels: *** = P < 0.001, ** = P < 0.01, * = P < 0.05 (Nallanchakravarthula et al., 2021)

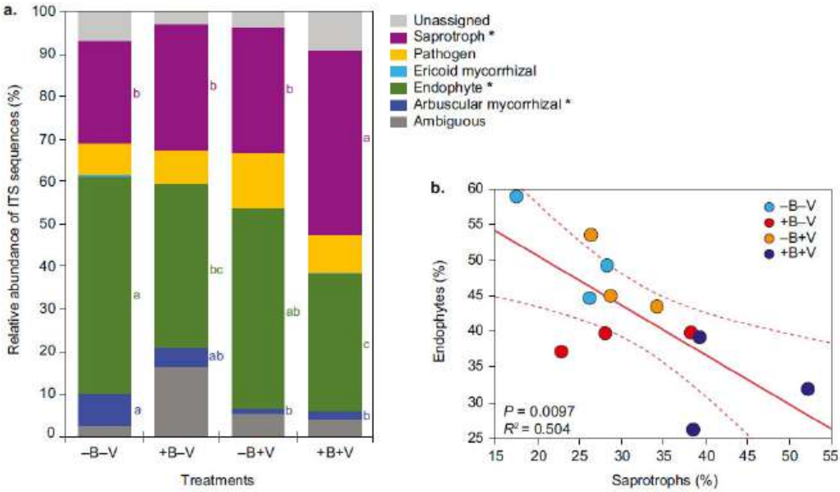

Figure 2.38 – Relative abundance of ITS sequences representing different functional guilds of fungi in roots of strawberry plants treated with factorial combinations of oilseed radish (*Raphanus sativus oleifera*) residues as biofumigant, (+/− B) and inoculation with the fungal pathogen *Verticillium dahliae* (+/− V) (a). Analysis of variance (ANOVA) significance level * = *P* < 0.05. Regression analysis of the proportion of ITS sequences belonging to endophyte and saprotroph functional guilds in the roots (b) show a statistically significant negative relationship between the two functional guilds. The dotted lines represent 95% confidence intervals (Nallanchakravarthula et al., 2021).

The antinematode effectiveness of oil radish has also been proven in terms of antinematode activity when growing vegetables in greenhouses. Thus, in the studies of Haroutunian (2013) was found that root-knot nematodes remain one of the most serious problems faced by greenhouse farmers of Lebanon and the Middle East region. The presence of these nematodes in the soil even in relatively small numbers causes serious damage to vegetable crops, specifically those lacking any resistance or tolerance to these pests, such as the cucurbits. In the past, soil fumigation with Methyl Bromide has been considered as the best control measure against root-knot nematodes.

However, Methyl Bromide was completely banned worldwide for Ozone preservation concerns. Biofumigation with the use of green manure crops has been one of the potential alternatives suggested by the Methyl Bromide Alternatives Project Lebanon. Under these circumstances, scientific evaluation of the efficiency and cost effectiveness of this technique in Lebanon is an important area of research.

As to the results achieved by the biofumigation crops with respect to Methyl Bromide, in experiment A yield produced by Methyl Bromide was significantly higher than oil radish with plastic cover. However, no significant difference was found between reduction of nematode population resulting from Methyl Bromide and oil radish with plastic cover. Difference was significant between Methyl Bromide and oil radish without plastic cover in both yield and reduction of nematodes (Figure 2.39).

In experiment B no significant difference was observed in neither yield nor reduction of nematode population between any of the two biofumigation crops used with plastic cover and Methyl Bromide. These differences were significantly in favor of Methyl Bromide only when oil radish was used without plastic cover.

In experiment C where Vydate (Oxamyl) was incorporated at the rate of 1 liter per 1,000 m^2 to all treatments, there was no significant difference in neither yield nor reduction of nematode population between any of the two biofumigation crops used with or without plastic cover and Methyl Bromide.

Cost-benefit analysis made on all treatments applied in the 3 experiments showed that in all cases, all these treatments whether chemical, non-chemical (with or without plastic cover) or in combination have produced higher net profits than Methyl Bromide, even when yield produced by Methyl Bromide was significantly higher.

Use of plastic for covering oilseed radish has generally produced better results in terms of production of higher yields, better reduction of soil populations of root-knot nematodes and leading to reasonable increases of net profits.

Based on these findings and in the light of global phase out of Methyl Bromide, it can be concluded that the use of oil radish and arugula as biofumigation crops with plastic cover can be considered as an alternative management tool for the root-knot nematode in greenhouse cucumber production under Lebanese conditions.

Besides adequate control of a wide range of nematodes and fungal diseases in the soil, biofumigation with the use of green manure crops presents several other major advantages. It improves soil texture and structure and increases organic matter and water holding capacity, doesn't harm most of the beneficial microorganisms of the soil and above all, it is one of the least expensive alternatives to Methyl Bromide. However, biofumigation has the major disadvantage of requesting a relatively a longer period of application time (45 days) as compared to Methyl Bromide (10 days). For most farmers this fact alone is a major handicap for the wide scale adoption of this technique as a viable alternative to Methyl Bromide.

Therefore, future research must focus on appropriate methods for the reduction of the application period of biofumigation crops. For this purpose, new fast growing varieties of oil radish (*Raphanus sativus oleífera*) and arugula (*Eruca vesicaria sativa*) producing more abundant vegetative parts within a shorter period of time, as well as other varieties of the Brassicaceae family must be developed and tested for their satisfactory performance under local conditions. The arugula cultivar tested in our research was a common variety purchased at the local market. It was till then used for rocket (salad) production purposes and its capacity as a biofumigant crop were unknown and not assessed. The results of our study indicate that arugula is worth of further development and additional testing is needed for the determination of its properties and eficacy as a biofumigant crop.

Finally, the combination of biofumigant crops with low doses of some chemical nematicides with limited impact on the environment remains a potential area of further investigation, having as purpose to evaluate new chemistry or to determine the minimal rates of the chemicals used in combination with the biofumigant crops and/or the maximum reduction of the application period of the biofumigation crops tested.

The second experiment (B) initiated immediately after the end of the following summer season in a greenhouse having the same area and adjacent to the one used in experiment A. The previous tomato crop was removed and the soil was plowed after the incorporation of preparatory organic and chemical fertilizers at usual rates. The total area of the greenhouse was divided into twenty (20) plots of 3.80 x 4.00 (15.20 m^2) for the application of the following five treatments with four replicates each:

– Control (untreated fallow).

– Methyl Bromide.

– Oilseed radish *(Raphanus sativus* spp. *oleifera)* variety "Boss" without plastic cover.

– Oilseed radish *(Raphanus sativus* spp. *oleifera)* variety "Boss" with plastic cover Arugula *(Eruca vesicaria* spp. *sativa)* with plastic cover.

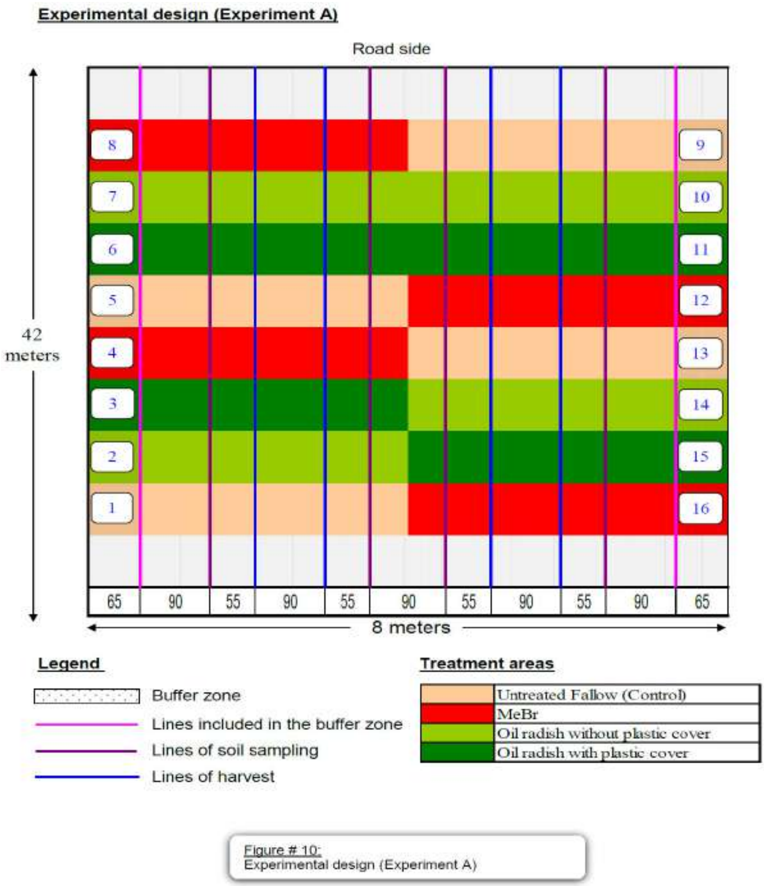

Figure 2.39 – Scheme of the experiment A (Haroutunian, 2013)

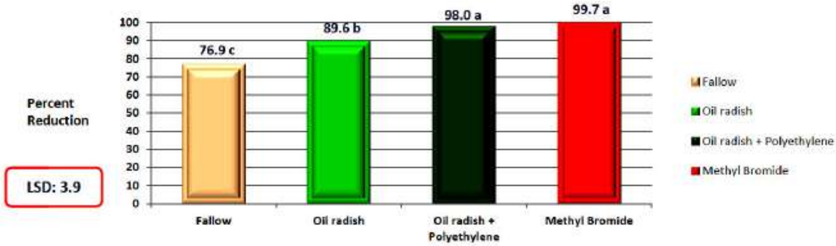

Figure 2.40 – Percent reduction of the soil population of root-knot nematodes (Experiment A) (Haroutunian, 2013)

In experiment B, the highest reduction was once again achieved with Methyl Bromide (99.7%). In plastic covered arugula or oil radish plots, M. incognita population was decreased by 97.7% and 94.2%, respectively, whereas in uncovered oil radish plots, population reduction was only 86.3%. In the untreated fallow, nematode population reduction was as low as 74.7% (Figure 2.41).

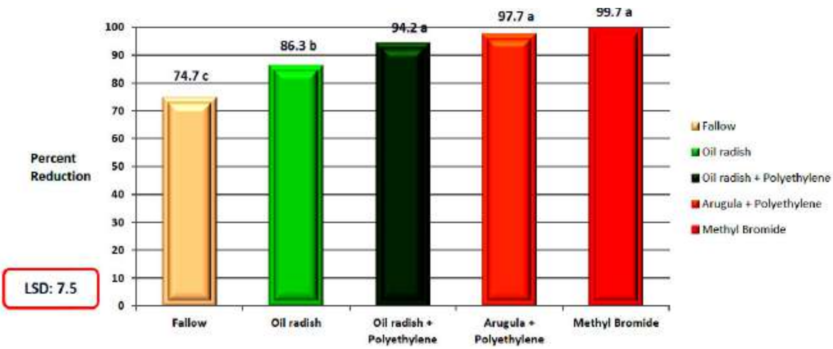

Figure 2.41 – Percent reduction of the soil population of root-knot nematodes (Experiment B) (Haroutunian, 2013)

In both experiments A and B, all treatments significantly reduced nematode population in comparison with the untreated fallow. Furthermore, there was no significant difference between the percent reduction of nematodes achieved by any of the two green manure crops (oil radish and arugula) covered with plastic and Methyl Bromide. When covered with 50 microns transparent polyethylene film immediately following their incorporation to the soil, both oil radish and arugula have been as effective as Methyl Bromide in reducing nematode population in the soil (Figure 2.40–2.41).

Generally, in both experiments A and B both biofumigation crops used significantly reduced nematode population as compared to untreated fallow (control). This result is conform to findings of other studies describing oil radish and arugula as non-hosts (or least poor hosts among a variety of biofumigant crops tested) to root-knot nematodes, causing decline of soil populations by starvation at the first place. Results of our experiments also match other studies having found that these biofumigation crops are able to control nematodes, and more specifically those having associated the nematostatic effect of biofumigation crops to the release of glucosinolates which soon convert into isothiocyanates in the soil and thus suppress nematode populations.

In both experiments A and B, plastic cover has significantly increased the efficiency of oil radish and lead to better nematode control. These results indicate that plastic cover enhances the effectiveness of the biofumigation crops used in terms of nematode control. It is to note that there was remarkable difference in the initial soil populations of nematodes in plots treated with covered and uncovered oil radish in each of these two experiments. In fact, the average initial infestation with root-knot nematodes in all eight plots treated with oil radish (covered and uncovered) at the site selected for experiment A was considerably more severe than in plots treated similarly at the site where experiment B was conducted, as shown in table # 1.1 below. Furthermore, whereas in experiment B the average initial infestation in plots treated with oil radish and covered with plastic was lower (865) than in plots treated with oil radish and kept without cover (3,475), in experiment A plots treated with oil radish and covered with plastic had considerably higher average initial infestation (12,430) than those of with oil radish without cover (7,310).

Our results indicate that use of plastic cover with oil radish significantly enhances the effectiveness of the isothiocyanates, leading to a better control of the root-knot nematode. The beneficial effect of the plastic is not related to the initial infestation levels. Furthermore, decreasing the covering period from 15 to 10 days does not negatively affect the efficiency of the plastic in the control of the root-knot nematode.

In experiment A root galling was significantly reduced by application of all treatments compared to fallow. The lowest root gall index was observed in the plots treated with Methyl Bromide (0.9). There was a significant reduction in the oil radish planted plots either covered with plastic or left uncovered compared to fallow. The gall reduction was less in plots planted with oil radish with or without plastic cover when compared to the untreated fallow plots (1.7 and 2.0 respectively). The highest galling was found in the roots of untreated fallow plots (7.1).

Figure 2.42 – Experiment A Galls on roots taken from the untreated fallow (A) & oil radish with plastic cover (B) (Haroutunian, 2013)

In experiment B root galling results were also quite similar to those of experiment A. On a scale of 1–10 the least root galling has occurred on plant roots taken from plots treated with Methyl Bromide (0.7). Galling on plant roots resulting from plastic covered arugula and oil radish plots was 1.7 and 2.4, respectively. Non-covered oil radish plots resulted into a root galling of 4.7, while roots taken from untreated fallow plots showed a gall index of 9.5.

Galls on roots taken from the different treatments: Methyl Bromide (A); arugula with plastic cover (B); oil radish with plastic cover (C); oil radish without plastic cover (D); untreated fallow (E) (Figure 2.44–2.45).

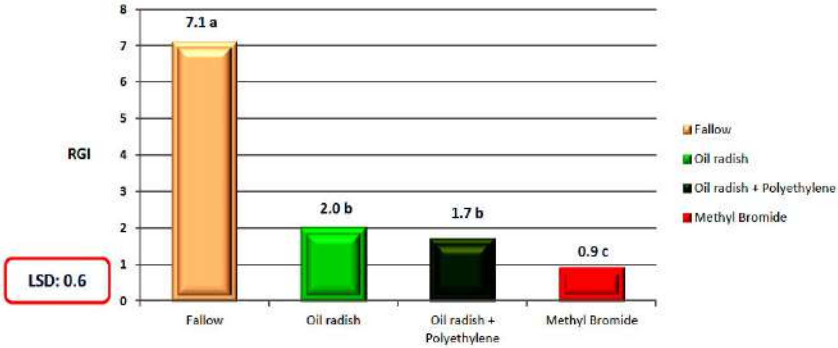

Figure 2.43 – Effect of different treatments on the cucumber root gall index at harvest (Experiment A) (Haroutunian, 2013)

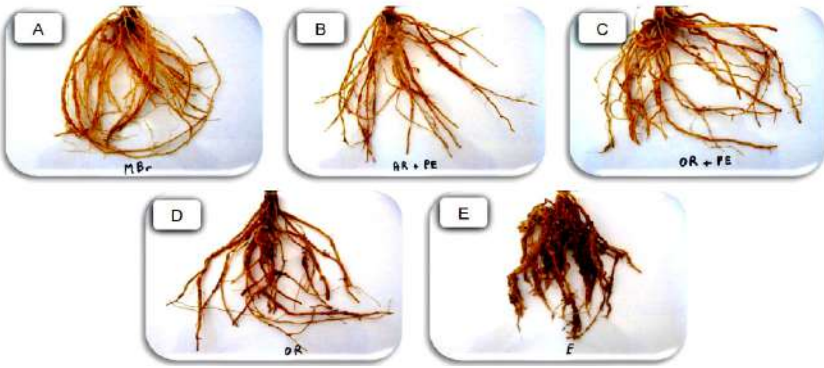

Figure 2.44 – (A, B, C, D, E): Experiment B (Haroutunian, 2013)

Both experiments A & B revealed similar results. Both biofumigation crops used significantly decreased root galls as compared to the untreated control. These results confirm the findings of several earlier studies classifying arugula and oil radish as non-host or poor host species to the root-knot nematode. The significant decline of root galls under the influence of these biofumigation crops justifies also the reduction of the soil population of the root-knot nematodes discussed earlier. Obviously, when there are no juveniles (J2) or active juveniles proliferating in the soil, the root gall formation on the roots of the crop will definitely reduce.

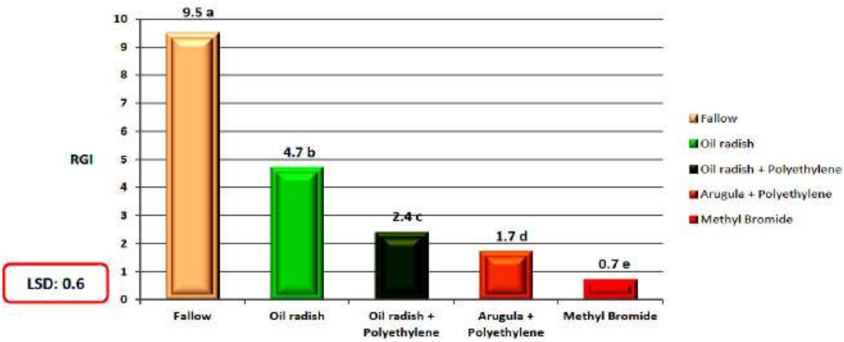

Figure 2.45 – Effect of different treatments on the cucumber root gall index at harvest (Experiment B) (Haroutunian, 2013)

These results further confirm that oil radish variety "Boss" and arugula can be considered as good cover crops and cause decline of the root-knot nematode population in the soil and on the roots of greenhouse cucumbers under Lebanese conditions. The efficacy of using sweet radish to reduce the number of beet cyst nematodes (BCN) and soybean cyst nematode (SCN) (Warner et al., 2017) has been demonstrated (Table 2.33–2.35).

Table 2.33

Average numbers of beet cyst nematode (BCN) females recovered per root system (number of trials in parentheses) (Warner et al., 2017)

Species	Common Name	Cultivar	BCN Females
1	2	3	4
Sinapsis alba	yellow mustard	Idagold (1)	267.75
Raphanus sativus	radish, tillage (1)		262.00
R. sativus	radish	Soilbuster (1)	220.25
R. sativus	radish	Driller (1)	211.25
R. sativus	radish	Daikon (1)	197.25
Brassica napus	rapeseed	Dwarf Essex (3)	190.00

(End of Table 2.33)

1	2	3	4
B. rapa	turnip, forage	Appin (3)	185.00
B. vulgaris	sugar beet	Prompt (1)	176.50
R. sativus	radish	Groundhog (3)	174.00
R. sativus	radish	Pile Driver (3)	173.58
B. juncea	brown mustard	Kodiak (3)	165.33
B. vulgaris	sugar beet	C-RR059 (1)	147.25
B. rapa	turnip, forage	Vivant (1)	137.75
R. sativus	radish	Graza (1)	135.25
S. alba	yellow mustard	Pacific Gold (2)	121.00
R. sativus	radish	GO-DRK (1)	87.00
B. oleracea	cabbage	Early Jersey Wakefield (1)	70.25
B. vulgaris	sugar beet	SX-1211NRR (1)	65.75
B. vulgaris	sugar beet	HM-50RR (1)	56.00
Phaseolus vulgaris	dry bean	Zorro (2)	26.58
R. sativus	radish	Carwoodi (3)	20.67
Raphanus sativus	radish	Cardinal (2)	7.00
Phaseolus vulgaris	dry bean	Puebla 152 (2)	5.88
R. sativus	radish	Toro(2)	5.75
Sinapsis alba	white mustard	Accent(3)	3.83
R. sativus	radish	Intermezzo (3)	2.40
S. alba	white mustard	Ludique (1)	1.75
R. sativus	radish	FumaRad (3)	1.33
Raphanus sativus	radish	Mercator (1)	0.75
R. sativus	radish	Tajuna (3)	0.58
R. sativus	radish	Image (2)	0.37
R. sativus	radish	Cannavaro (1)	0.25
R. sativus	radish	Defender: home grown (2)	0.25
R. sativus	radish	Maximus (1)	0.25
R. sativus	radish	Respect(2)	0.25
R. sativus	radish	Defender: certified (3)	0.13
Medicago sativa	alfalfa	Foregrazer (1)	0.00
Trifolium incarnatum	crimson clover (1)		0.00
T. pratense	red clover	Dynamite (1)	0.00
T. repens	white clover	Domino (1)	0.00

Table 2.34

Mean numbers of sugarbeet cyst nematode cysts, eggs and second-stage juveniles, eggs/cyst and males recovered from 100 cm³ soil in a greenhouse study after 8 weeks (Warner et al., 2017)

		sucarbeet cyst nematodes/100 cm³ soil						
		cysts		eggs + J_{2s}		eggs/cyst	males	
species	**Cultivar**	**X**	**SE**	**X**	**SE**	**X**	**X**	**SE**
cabbage	Early Jersey Wakefield	70.00	10.37	16860.00	3305.89	222.14	47.00	11.73
white mustard	Accent	1.50	0.75	220.00	110.00	146.17	1.00	0.50
mustard	Caliente 199 Blend	28.50	5.14	6572.50	1249.04	208.33	25.00	6.08
brown mustard	Kodiak	38.50	0.85	8210.00	517.84	181.04	107.00	18.17
yellow mustard	Pacific Gold	49.00	3.68	11730.00	691.73	208.98	57.00	3.30
oilseed radish	Cannava ro	0.50	0.14	133.50	44.63	265.00	1.00	0.50
oilseed radish	Carwoodi	3.75	0.94	497.50	100.36	109.33	0.50	0.25
oilseed radish	Defender[1]	0.00	0.00	0.00	0.00		3.00	0.96
oilseed radish	Defender[2]	0.00	0.00	0.00	0.00		5.00	1.50
oilseed radish	FumaRad	0.25	0.13	25.00	12.50	90.00	0.00	0.00
oilseed radish	Ground Hog	24.00	2.09	3950.00	749.31	137.92	78.00	13.33
oilseed radish	Intermezzo	1.00	0.20	234.00	43.57	227.50	0.00	0.00
oilseed radish	Pile Driver	42.25	3.03	7280.00	805.15	146.04	98.00	4.65
oilseed radish	Respect	0.25	0.13	50.00	25.00	200.00	4.00	0.71
oilseed radish	Taj una	1.00	0.29	132.50	40.49	122.50	7.00	2.50
oilseed radish	Toro	5.25	1.28	620.00	117.26	99.05	3.5	0.85
fodder turnip	Appin	31.25	6.66	5880.00	1475.81	165.44	81.00	13.91
turnip	Shogoin	14.00	1.21	2610.00	290.47	177.14	31.00	3.10

Table 2.35

Average numbers of soybean cyst nematode (SCN) cysts, eggs + second-stage juveniles per 100 cc soil on soybean (Pioneer 92Y91) following growth of the plants provided in the table (PI = 13050 SCN eggs + J2s) (Warner et al., 2017)

Plant	Cultivar	Tarp (Y/N)	cysts	Eggs + J2s	Pf/Pi
African marigold	Crackerjack	Y	112.50	13090	1.003
African marigold	Crackerjack	N	86.00	11840	0.907
annual ryegrass	Gulf	Y	104.25	13080	1.002
annual ryegrass	Gulf	N	82.00	12090	0.926
crimson clover		Y	102.50	13600	1.042
crimson clover		N	73.75	8640	0.662
yellow mustard	Pacific Gold	Y	59.00	7430	0.569
yellow mustard	Pacific Gold	N	35.50	4665	0.357
oilseed radish	FumaRad	Y	108.00	15040	1.152
oilseed radish	FumaRad	N	50.75	6820	0.523
rapeseed	Dwarf Essex	Y	80.25	10360	0.794
rapeseed	Dwarf Essex	N	102.00	13160	1.008
soybean	Pioneer 92Y91	Y	91.00	12270	0.940
soybean	Pioneer 92Y91	N	92.75	15220	1.166
fallow			157.25	15335	1.175
red clover	Medium red	Y	79.25	11295	0.866
red clover	Medium red	N	37.25	5085	0.390

Studies by Melakeberhan et al. (2008) and Edwards and Ploeg (2014) determined the effectiveness of oil radish against other nematode species (Table 2.36-2.37).

Table 2.36

Root galling and Meloidogyne incognita second-stage root-knot nematode juvenile numbers 8 wk after inoculating brassicaceous cultivars and tomato with 20,000 eggs (N = 5) per 3.8-liter pot. Ranking from 1 (highest) to 32 (lowest). (Melakeberhan et al., 2008; Edwards and Ploeg, 2014)

Species	Cultivar	Galling		*p*	Ranking	J2/100 g		*p*	Ranking
Experiment 1									
Brassica carinata	Bc007	3.4	(±0.2)[a]	hijk	13	502	(±57)[a]	fghij	18
Brassica juncea	ISCI99	5.0	±0.3)	de	5	2,422	± 540)	abc	4
	Nemfix	6.2	±0.4)	bc	3	2,134	±221)	abcd	5
	Pacific Gold	6.4	±0.5)	b	2	3,226	±1,174)	ab	2
Brassica napus	Greenland	3.8	±0.4)	fghi	10	566	± 149)	fghij	12
	Humus	3.0	±0.5)	ijkl	14	1,079	± 207)	cdefg	9
	Winfred	2.6	±0.2)		22	554	± 130)	fghij	15
Brassica oleracea	Liberty	1.0	±0.0)	op	31	9	± 2)	o	31
Brassica rapa	Br02205	4.6	±0.2)	def	6	995	± 205)	defg	10
	Br02206	5.4	±0.2)	cd	4	2,423	± 745)	abcd	3
	Rondo	4.4	±0.4)	efg	7	1,084	±210)	cdef	8
	Samson	4.2	±0.4)	efgh	8	1,369	± 355)	bcde	6
Eruca sativa	Nemat	3.6	±0.2)	ghij	11	267	±79)	jklm	25
Oilseed radish (Raphanus sativus)	Adagio	2.6	±0.2)	klm	23	141	±18)	lm	29
	Adios	4.2	±0.4)	efgh	9	277	±65)	ijkl	24
	Boss	0.4	±0.2)	p	32	7	± 5)	o	32
	Colonel	3.0	±0.5)	ijkl	15	201	± 64)	klm	27
	Comet	3.6	±0.2)	ghij	12	190	± 81)	mn	28
	Defender	2.8	±0.4)	jkl	17	257	± 70)	jklm	26
	Doublet	2.2	±0.2)	lmn	28	556	±107)	efghi	13
	Final	3.0	±0.3)	ijkl	16	468	±156)	hijk	21
	Rs05415	2.8	±0.4)	jkl	18	284	± 70)	ijkl	23
	TerraNova	2.6	±0.2)	klm	24	63	±19)	n	30
Sinapis alba	Abraham	1.6	±0.2)	no	30	351	± 59)	hijkl	22
	Absolut	2.8	±0.2)	jkl	19	546	±46)	efghi	16
	Accent	1.8	±0.2)	mno	29	648	±105)	efgh	11
	Achilles	2.6	±0.2)	klm	25	487	±106)	fghij	19
	Condor	2.8	±0.4)	jkl	20	1,234	±163)	bcde	7
	IdaGold	2.8	±0.2)	jkl	21	480	± 98)	ghij	20
	Maxi	2.4	±0.2)	lmn	26	554	± 140)	fghij	14
	Santa Fe	2.4	±0.2)	lmn	27	505	± 180)	hijk	17
Solanum lycoper-sicum	UC82	7.6	±0.2)	a	1	4,271	±1,092)	a	1

(End of Table 2.36)

Experiment 2									
Brassica carinata	Bc007	3.4	±0.2)	ghi	12	316	±76)	defgh	17
Brassica juncea	ISCI99	5.6	±0.2)	cd	4	662	±68)	bcde	7
	Nemfix	6.6	±0.7)	b	2	1,630	± 849)	bc	3
	Pacific Gold	6.4	±0.5)	bc	3	1,273	± 813)	bcd	4
Brassica napus	Greenland	3.4	±0.2)	ghi	13	180	±21)	fghi	22
	Humus	1.8	±0.4)	ijkl	27	240	±73)	fghi	21
	Winfred	2.6	±0.2)	ijkl	20	172	±41)	fghij	23
Brassica oleracea	Liberty	0.6	±0.2)	op	32	0	± 0)	k	32
Brassica rapa	Br02205	5.0	±0.3)	de	6	360	± 115)	defgh	14
	Br02206	5.4	±0.4)	d	5	2,624	± 1,448)	ab	2
	Rondo	4.4	±0.2)	ef	7	458	± 298)	defgh	9
	Samson	4.4	±0.2)	ef	8	1,088	± 483)	bcde	5
Eruca sativa	Nemat	3.4	±0.2)	ghi	14	164	± 59)	hij	25
Oilseed radish (Raphanus sativus)	Adagio	3.4	±0.2)	ghi	15	116	± 29)	hij	27
	Adios	4.2	±0.2)	efg	9	308	±78)	defgh	18
	Boss	0.8	(±0.4)	p	31	6	±4)	k	31
	Colonel	3.0	(±0.0)	hij	17	164	±50)	fghij	24
	Comet	4.2	(±0.4)	efg	10	142	(±36)	ghij	26
	Defender	2.6	(±0.2)	ijkl	21	74	±42)	j	30
	Doublet	2.6	(±0.2)	ijkl	22	408	±128)	cdefgh	11
	Final	3.8	(±0.4)	fgh	11	422	(±111)	cdefg	10
	Rs05415	3.2	(±0.4)	hij	16	390	±152)	efgh	12
	TerraNova	2.8	(±0.2)	ijk	18	80	(±46)	j	29
Sinapis alba	Abraham	1.4	(±0.2)	no	30	88	(± 34)	ij	28
	Absolut	2.8	(±0.4)	ijk	19	332	(±230)	fghi	15
	Accent	2.0	(±0.5)	mno	25	324	(±63)	defgh	16
	Achilles	1.8	(±0.2)	klm	28	912	(±495)	cdef	6
	Condor	2.0	(±0.3)	jkl	26	304	(± 64)	defgh	19
	IdaGold	2.6	(±0.2)	ijkl	23	518	(±353)	fghi	8
	Maxi	1.8	(±0.4)	lmn	29	286	(±95)	defgh	20
	Santa Fe	2.4	(±0.2)	jkl	24	372	±190)	defgh	13
Solanum lycoper-sicum	UC82	7.8	(±0.2)	a	1	5,460	(±1,816)	a	1

a Values shown are the mean of five replicates (n = 5) ± SE. Root galling index on a scale from 0 to 10 with 0 = no galls, 10 = 100% of roots galled. Values in a column followed by different letters are significantly different (P # 0.05) according to Fisher's LSD-test within one experiment. Raw nematode data (egg counts) were log10(x+1)-transformed before analysis; nontransformed data are presented.

Table 2.37

Root galling and *Meloidogyne javanica* second-stage root-knot nematode juvenile numbers 8 wk after inoculating brassicaceous cultivars and tomato with 20,000 eggs (N = 5) per 3.8-liter pot. Ranking from 1 (highest) to 32 (lowest) (Melakeberhan et al., 2008; Edwards and Ploeg, 2014)

Species	Cultivar	Galling		*p*	Ranking	J2/100 g		*p*	Ranking
Experiment 1									
Brassica carinata	Bc007	4.0	(±0.3)[a]	gh	11	552	(±95)[a]	jk	25
Brassica juncea	ISCI99	6.0	±0.3)	cde	5	3,816	±1,070)	abcde	6
	Nemfix	7.0	±0.3)	b	2	3,980	±966)	abcd	4
	Pacific Gold	6.0	±0.5)	cde	6	2,812	±806)	bcdefg	11
Brassica napus	Greenland	4.8	±0.4)	fg	9	1,972	± 445)	defgh	13
	Humus	3.4	±0.2)	hij	14	1,620	±303)	efgh	17
	Winfred	5.8	±0.2)	de	7	3.096	±809)	abcdef	10
Brassica oleracea	Liberty	1.6	±0.2)	no	30	1,584	±413)	fghi	18
Brassica rapa	Br02205	6.8	±0.4)	bc	3	3,868	±819)	abcd	5
	Br02206	6.6	±0.2)	bcd	4	4,684	± 874)	abc	3
	Rondo	4.8	±0.4)	fg	10	6,524	±1,723)	a	1
	Samson	5.2	±0.4)	ef	8	3,584	±1,082)	abcdef	8
Eruca sativa	Nemat	3.0	±0.3)	ijkl	18	144	±76)	l	29
Oilseed radish (Raphanus sativus)	Adagio	3.2	±0.4)	hijk	17	450	±106)	k	28
	Adios	3.6	±0.4)	hi	12	1,280	±302)	ghi	19
	Boss	0.4	±0.2)	p	32	92	±48)	l	32
	Colonel	2.6	±0.4)	jklm	20	646	±73)	ijk	24
	Comet	3.4	±0.2)	hij	13	1,816	± 384)	defgh	15
	Defender	2.6	±0.2)	jklm	21	122	±52)	l	30
	Doublet	1.6	±0.2)	no	29	508	±166)	k	27
	Final	2.2	±0.4)	lmno	24	1,008	± 248)	ijk	21
	Rs05415	2.2	±0.2)	jkl	25	552	±121)	jk	26
	TerraNova	3.0	±0.3)	lmno	19	96	±26)	l	31
Sinapis alba	Abraham	2.2	±0.4)	lmno	23	3,544	±575)	abcde	9
	Absolut	3.2	±0.6)	hijk	15	1,620	±323)	efgh	16
	Accent	1.8	±0.2)	mno	27	732	±193)	ijk	23
	Achilles	3.2	±0.4)	hijk	16	3,708	±1,423)	abcdef	7
	Condor	2.4	±0.2)	klmn	22	2,526	±556)	cdefg	12
	IdaGold	2.0	±0.5)	mno	26	1,896	±477)	defgh	14
	Maxi	1.4	±0.2)	o	31	1,256	±329)	ghij	20
	Santa Fe	1.8	±0.2)	mno	28	908	± 84)	hij	22
Solanum lycopersicum	UC82	8.0	±0.3)	a	1	6,120	±1,405)	ab	2

(End of Table 2.37)

Experiment 2									
Brassica carinata	Bc007	2.8	±0.2)	de	7	74	±24)	mn	26
Brassica juncea	ISCI99	2.4	±0.2)	efg	11	1,364	± 449)	abc	3
	Nemfix	4.4	±0.3)	b	2	1,628	±575)	ab	2
	Pacific Gold	3.4	±0.8)	cd	5	670	±291)	bcdefg	11
Brassica napus	Greenland	2.0	±0.0)	efghi	17	602	±104)	bcdefg	13
	Humus	2.2	±0.5)	efgh	14	848	±119)	abcde	7
	Winfred	2.8	±0.4)	de	9	728	±126)	bcdef	9
Brassica oleracea	Liberty	1.0	±0.3)	jkl	29	8	±6)	pq	30
Brassica rapa	Br02205	3.4	±0.4)	cd	4	74	±12)	klm	27
	Br02206	2.8	±0.5)	de	8	954	± 444)	bcdefg	5
	Rondo	3.4	±0.2)	cd	6	972	±153)	abcd	4
	Samson	3.8	±0.2)	bc	3	754	±79)	bcdef	8
Eruca sativa	Nemat	1.0	±0.5)	jkl	30	44	±30)	op	28
Oilseed radish (Raphanus sativus)	Adagio	1.2	±0.4)	ijk	25	222	±95)	ijkl	20
	Adios	2.2	±0.2)	efgh	13	858	±106)	abcde	6
	Boss	0.2	(±0.2)	l	32	6(	±3)	pq	31
	Colonel	1.8	(±0.6)	fghij	19	150 (	± 104)	lmn	23
	Comet	1.4	(±0.2)	hij	24	722 (	±153)	bcdefg	10
	Defender	0.4	(±0.2)	kl	31	4(	±2)	q	32
	Doublet	5.6	(±0.2)	bcd	20	486 (	± 184)	cdefgh	14
	Final	1.2	(±0.2)	ijk	26	330 (	± 97)	defghi	17
	Rs05415	1.2	(±0.4)	ijk	27	86 (	± 15)	jklm	25
	TerraNova	1.2	(±0.4)	ijk	28	40 (	± 15)	no	29
Sinapis alba	Abraham	1.8	(±0.4)	fghij	18	400 (	± 149)	defghi	15
	Absolut	2.6	(±0.4)	def	10	254 (	± 69)	fghijk	19
	Accent	1.6	(±0.2)	ghij	22	108 (	±27)	ijklm	24
	Achilles	1.4	(±0.2)	hij	23	274 (	± 24)	efghij	18
	Condor	2.0	(±0.3)	efghi	16	220 (	± 64)	ghijk	21
	IdaGold	1.8	(±0.4)	fghij	21	640 (	± 153)	bcdefgh	12
	Maxi	2.2	(±0.4)	efgh	15	208 (	±110)	hijkl	22
	Santa Fe	2.4	(±0.5)	efg	12	384 (	± 96)	cdefgh	16
Solanum lycopersicum	UC82	7.2	(±0.2)	a	1	2,840 (	± 443)	a	1

a Values shown are the mean of five replicates (n = 5) ± SE. Root galling index on a scale from 0 to 10 with 0 = no galls, 10 = 100% of roots galled. Values in a column followed by different letters are significantly different (P # 0.05) according to Fisher's LSD-test within one experiment. Raw nematode data (egg counts) were log10(x+1)-transformed before analysis; nontransformed data are presented.

This results (Melakeberhan et al., 2008; Edwards and Ploeg, 2014) showed that there are significant differences within and between brassicaceous species with regard to host status for RKNs, and furthermore that the host suitability of a particular brassicaceous cultivar for RKNs can differ depending on the nematode species. Therefore, identifcation of the target RKN to species level is important to optimize this management strategy. Results for *M. incognita* and *M. javanica* were similar, with *B. juncea* and *B. rapa* cultivars generally being good hosts, and *E. sativa* Nemat and the *R. sativus* (oilseed radish) cultivars Boss and TerraNova consistently ranking among the poorest hosts. Whether inoculated with M. incognita or *M. javanica*, reproduction on the latter two cultivars was reduced by at least 98% compared with reproduction on tomato. These results are in agree¬ment with findings by Curto et al. (2005) who also reported that *B. juncea* cultivars were among the better hosts for *M. incognita*, and that R. sativus (oilseed radish) Boss and E. sativa Nemat were poor or nonhost. Broccoli, in our study a poor host for *M. incognita* and to a lesser degree for *M. javanica* as a crop that showed potential to reduce Meloidogyne populations, although they used a different cultivar. *Brassica juncea* Nemfix, in our study among the best hosts for *M. incognita* and *M. javanica*.

Also was concluded that information on the level of susceptibility of Brassica species to RKN is needed for biofumigation to become a succesful nematode management strategy. The *R. sativus* (oilseed radish) cultivar Adagio, in our study a poor host for both *M. incognita* and *M. javanica*/

The response of M. hapla to the different brassica cultivars was sometimes very different from results with *M. incognita* or *M. javanica*. For example, *R. sativus* (oilseed radish) Colonel and TerraNova were among the best hosts for *M. hapla*, but poor hosts for *M. incognita* and *M. javanica*. Also, the variability in host status for *M. hapla* within the same brassica species was greater. For example, within *R. sativus* (oilseed radish) there were good hosts (Colonel, TerraNova) as well as poor hosts (Adagio, Condor). The fact that plants resistant to *M. incognita* and *M. javanica* are often susceptible to *M. hapla* is thought to be the result of basic differences in the inheritance of resistance.

Within *R. sativus* (oilseed radish) lines, it is also thought that differences in reponse to *M. incognita* or *M. javanica*, and *M. hapla* may be because of a single gene resistance mechanism for the former two species, and a polygenic resistance mechanism for *M. hapla*. Ongoing breeding efforts may lead to more cultivars with resistance to the range of economically inportant Meloidogyne species. In this study (Melakeberhan et al., 2008; Edwards and Ploeg, 2014) poor hosts for all three Meloidogyne species include *R. sativus* (oilseed radish) Adagio and E. sativa Nemat.

Although this study did not include the biofumigant effect that occurs during cover crop decomposition after soil incorporation of the crop, it would be unproductive to grow a host crop as a biofumigant. This study clearly demonstrated that large differences occur between different brassica cultivars with respect to their host status for three Meloidogyne species. Based on this study, the *R. sativus* (oilseed radish) cultivars Boss, Terranova, or *E. sativa* Nemat would be good choices for cover crops on *M. incognita* – or *M. javanica*-infested sites. Conversely, *B. rapa* or *B. juncea* cover crops would carry a risk of substantial nematode multiplication. On *M. hapla*-infested sites, *E. sativa* Nemat would carry little risk of nematode multplication, whereas *B. juncea* cultivars should be avoided.

The use of oilseed radish as a biofumigant against soil pathogens in potato cultivation has been found to be effective. Thus, in studies (Laznik et al., 2014) it was found that Brassica crops and their secondary metabolites on the wireworm population dynamics in soil. The analysis was based on sampling seven different glucosinolates. By the quantity detected, three glucosinolates stood out: glucoiberin, glucotropin and gluconasturtiin. It was found out that among different Brassica crops there are differences in the amount of glucoiberin. Significantly, the highest amount of glucoiberin was confirmed in samples of white mustard (5.54 ± 0.01 μmol/g ds), whereas the lowest values were confirmed in rapeseed (0.82 ± 0.01 μmol/g ds; Figure 2.46). Based on our results, we conclude that the amount of gluconas-turtiin is not influenced by a specific Brassica plant species (P = 0.8258). In the beginning, the content of gluconasturtiin in the samples of white mustard was 62 ± 0.22 μmol/g, while in the samples of rapeseed was 1.13 ± 0.55 μmol/g ds. Also the concentration of the glucobrassicin differed between different Brassica species. The values ranged between 0.25 ± 0.01 ^mol/g ds (white mustard) and 0.45 ± 0.00 μmol/g ds (kale; Figures 2.46–2.48).

Figure 2.46 – Average values of glucosinolates in tested cruciferous species (μmol/g ds). Different small letters indicate significant differences (*P < 0.05*, Student-Newman-Keuls' multiple range test) of different

glucosinolates content within the same cruciferous species. Different capital letters indicate significant differences between tested cruciferous species in the amount of glucosinolates (Laznik et al., 2014)

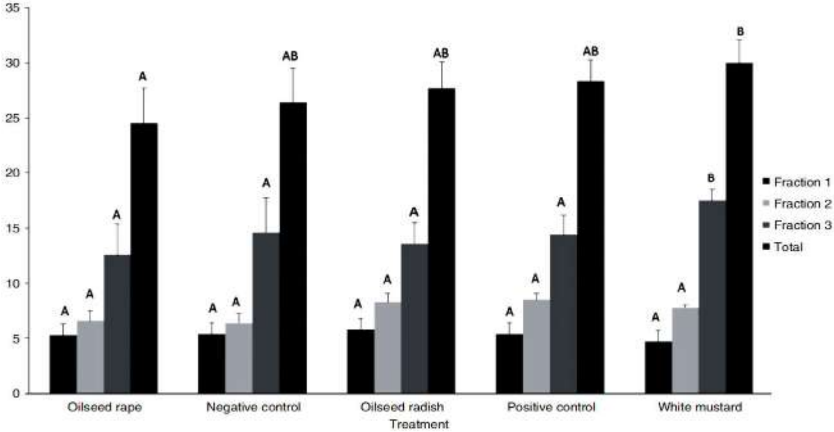

Figure 2.47 – The effect of different treatments on potato yield in 2011 in t ha-1. Different capital letters indicate significant differences (*P < 0.05*, Student-Newman-Keuls' multiple range test) within different treatments at the same fraction. Fraction 1 (tubers <4 cm); fraction 2 (tubers between 4 cm and 5 cm) and fraction 3 (tubers >5 cm)

ANOVA of pooled results in 2011 indicated a statistically significant effect of treatment (F = 3.61; df = 4, 149; P = 0.0080) and edge effect (F = 59.57; df = 2, 149; P < 0.0001) on the number of wireworm holes per potato tuber. In 2012, there were no significant differences among different treatments (F = 0.95; df = 6, 83; P = 0.4728) and edge effect (F =1.11; df = 3, 83; P = 0.3572) on the number of wireworm holes per potato tuber.

In 2011, there were significantly low number of wireworm holes per potato tuber in positive control (1.20 ± 0.3) and highest at white mustard (4.1 ± 1.1). Among other treatments, there were no significant differences and the number of holes per potato tuber ranged from 2.6 ± 0.7 (negative control) to 3.4 ± 0.9 (rapeseed; Figure 2.49). The edge effect influenced the injuries rate of potato tubers in 2011. There was significantly low number of wireworm holes in potato in the right edge of the field (0.38 ± 0.1). In the middle part of the field, on average, 1.46 ± 0.2 holes per potato were found. The highest number of wireworm holes per potato was found in the left edge of the field (6.8 ± 0.9; Figure 2.50).

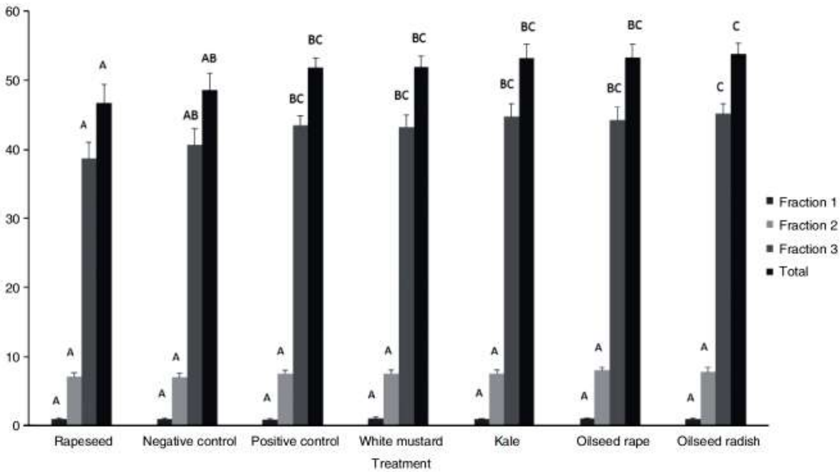

Figure 2.48 – The effect of different treatments on potato yield in 2012 in t ha^{-1}. Different capital letters indicate significant differences (*P < 0.05*, Student-Newman-Keuls' multiple range test) within different treatments at the same fraction. Fraction 1 (tubers <4 cm); fraction 2 (tubers between 4 cm and 5 cm); fraction 3 (tubers >5 cm)

In 2012, there were significantly low number of wireworm holes per potato tuber in rapeseed (0.22 ± 0.07) and kale (0.25 ± 0.04). Among other treatments, there were no significant differences, and the number of holes per potato tuber ranged from 0.39 ± 0.03 (negative control) to 0.47 ± 0.06 (positive control; Figure 2.51).The edge effect also did not have any influence on the number of wireworm holes per potato tuber in 2012, and the values ranged from 0.27 ± 0.03 (left edge of the field) to 0.45 ± 0.05 in the middle part of the field (Figure 2.52).

In both the years, big tubers (fraction 3) were significantly more damaged (2011: 1.69 ± 0.12 holes per potato tuber; 2012: 0.19 ± 0.04 holes per potato tuber) than smaller tubers [fraction 2 (2011: 0.93 ± 0.16 holes per potato tuber; 2012: 0.11 ± 0.02 holes per potato tuber) and Fraction 1 (2011: 0.24 ± 0.06 holes per potato tuber; 2012: 0.06 ± 0.02 holes per potato tuber)].

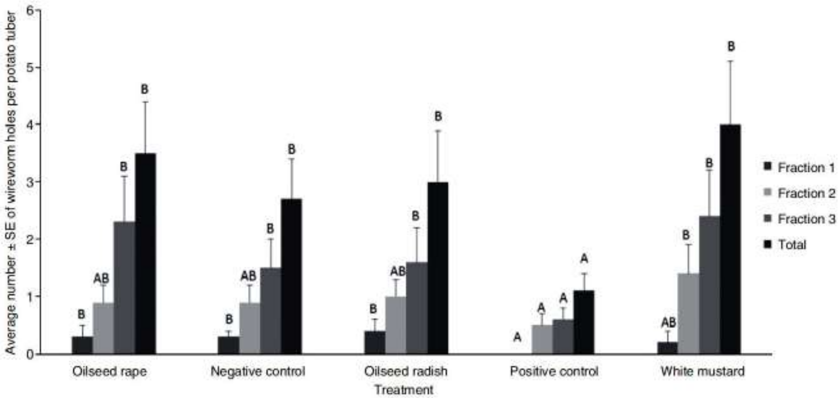

Figure 2.49 – The effect of different treatments on the average number of wireworm holes per potato tuber at different fractions in 2011. Different capital letters indicate significant differences (*$P < 0.05$*, Student-Newman-Keuls' multiple range test) within different treatments at the same fraction. Fraction 1 (tubers <4 cm); fraction 2 (tubers between 4 cm and 5 cm) and fraction 3 (tubers >5 cm)

The antinematode efficacy of oilseed radish has also been confirmed by other researchers (Menna and Melakeberhan, 2006; Hemayati et al., 2017; Hamidi and Hajihassani, 2020) (Figure 2.53-2.54).

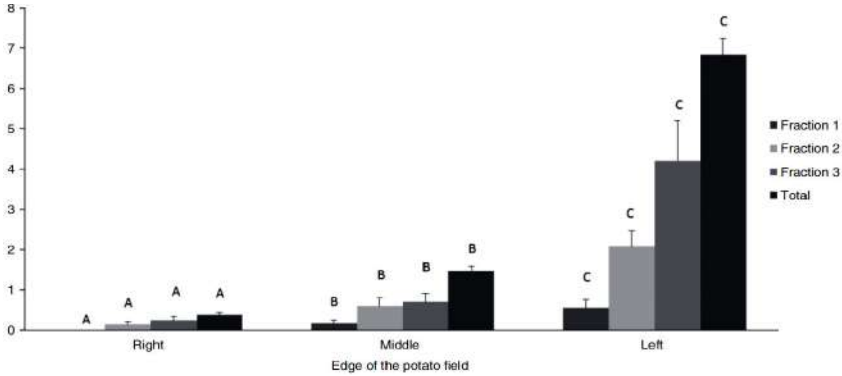

Figure 2.50 – The effect of the edge of the potato field on the average number of wireworm holes per potato tuber in 2011. Different capital letters indicate significant differences (*P < 0.05*, Student-Newman-Keuls' multiple range test) within the edge of the potato field at the same fraction. Fraction 1 (tubers <4 cm); fraction 2 (tubers between 4 cm and 5 cm) and fraction 3 (tubers >5 cm)

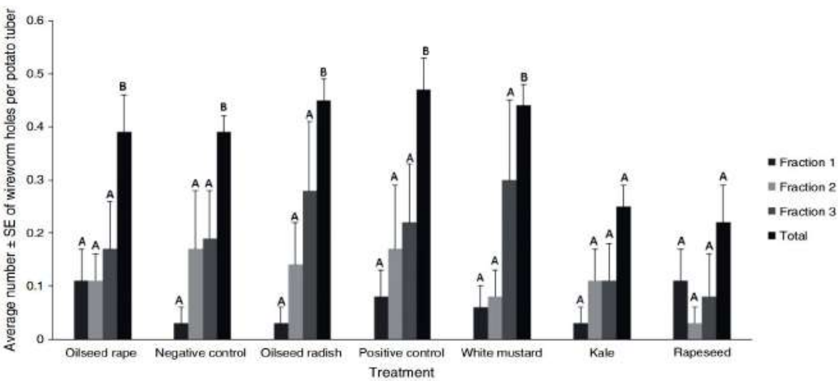

Figure 2.51 – The effect of different treatments on the average number of wireworm holes per potato tuber at different fractions in 2012. Different capital letters indicate significant differences (*P < 0.05*, Student-Newman-Keuls' multiple range test) within different treatments at the same fraction. Fraction 1 (tubers <4 cm); fraction 2 (tubers between 4 cm and 5 cm) and fraction 3 (tubers >5 cm)

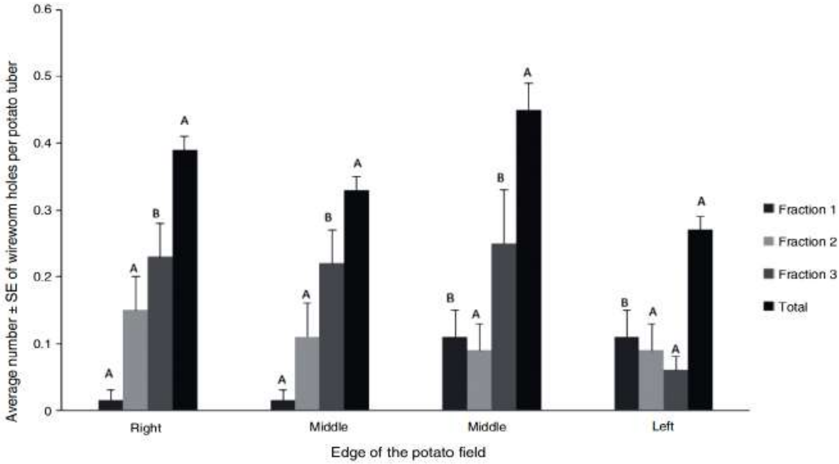

Figure 2.52 – The effect of the edge of the potato field on the average number of wireworm holes per potato tuber in 2012. Different capital letters indicate significant differences ($P < 0.05$, Student-Newman-Keuls' multiple range test) within the edge of the potato field at the same fraction. Fraction 1 (tubers <4 cm); fraction 2 (tubers between 4 cm and 5 cm) and fraction 3 (tubers >5 cm)

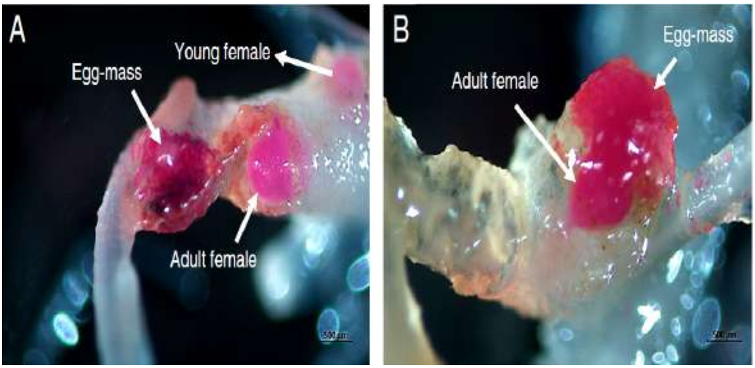

Figure 2.53 – Representative images of roots of oilseed radish cv. Eco-Till (A) and oat cv. Pratex (B) infected with Meloidogyne arenaria at 28 days after inoculation (Hamidi and Hajihassani, 2020)

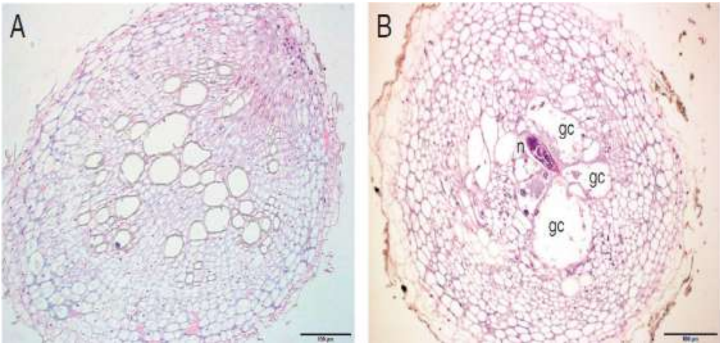

Figure 2.54 – Hematoxylin-Eosin stained cross sections of root tissues of oilseed radish cv. Carwoodi (A) and Eco-Till (B) infected with Meloidogyne incognita at 28 days after inoculation. N, female nematode; GC, giant cell (Hamidi and Hajihassani, 2020)

Oilseed radish stands out positively among other crops, which significantly reduces the number of nematodes when growing nematode-resistant varieties (Table 2.38) (Babych et al., 2011).

Table 2.38

Effect of nematode-resistant oil radish varieties on nematode abundance when grown as a main crop (Lykhochvor, 2008)

Variety	Originator	Impact on beet nematode population (+ increase, - decrease)	Flowering rate: 9 – high 1 – small	Mass growth rate: 9 – high 1 – small	Plant height: 9 – large 1 – small
Adagio	Saaten Union	- 70 – 90 %	2	5	2
Pegletta	Saaten Union	- 70 – 90 %	7	6	5
Colonel	Saaten Union	- 90 % і більше	5	5	4
Roma	St. Ramenda	- 90 %	5	5	5

The effective nematode-regulating role of oil radish has been proven, and the greatest inhibitory effect was provided by the use of oil radish as a green manure in combination with the resistance of the host plant. The lowest cyst viability was found in the variant with the use of oil radish green manure and a nematode-resistant potato variety (Table 2.39).

Table 2.39

Population density and viability of cystic fibrosis under different methods of substrate treatment (Babich et al., 2011)

Variant	Number of new generation cysts, pcs./100 g of soil	Reproduction rate	Cyst viability, %
1. Nevsky variety (K)	3.7	0.55	89
2. Sante variety	1.3	0.20	85
3. Oilseed radish (green manure)	2.0	0.30	75
4. Oilseed radish + Nevsky variety	1.0	0.15	92
5. Oilseed radish + Sante variety	0.3	0.05	83
LSD_{05}	1.1		

* – deviations from the control are significant $F_{fact} > F_{theor}$ (2.61).

The influence of green manure and biofumigation use of oilseed radish leaf mass in variants of influence on the microbiological activity of the soil profile was also proved. Thus, the studies Aiyer et al. (2022) have established that ITS1 sequencing produced a total of 69 005 920 reads from 360 samples. After trimming and chimera screening, a total of 28407 646 clean reads were clustered into 23 576 OTUs, of which 1356 OTUs remained after filtering out unclassified and low-abundance OTUs. Of the 1356 OTUs, 752 were predicted based on the reference database and 604 were de novo annotated. The most abundant fungal taxa identified at the family level were Plectosphaerellaceae (Fig. 2.55 A). Differences in abundance of fungal OTUs at different sample collection time points were observed at the family level (Fig. 2.55 B). An increase in abundance of Nectriaceae spp. in the cash crop phase of the second trial was also observed (Fig. 2.55 B).

Bacterial communities were characterized by sequencing the 16S rRNA gene, resulting in a total of 1 284 705 reads and 1 029 658 filtered and nonchimeric reads, with an average read length of 1451 bp, which clustered into 62 204 OTUs. After filtering based on low abundance and taxonomy, a total of 10 799 OTUs remained, of which 9967 were predicted based on the reference database, whereas 832 were de novo annotated. Bacillaceae was the most abundant bacterial family in the soil (Figure 2.56 A). Unlike with fungi, bacterial community relative abundance between sample collection time points was highly conserved at the family level (Fig. 2.56 B).

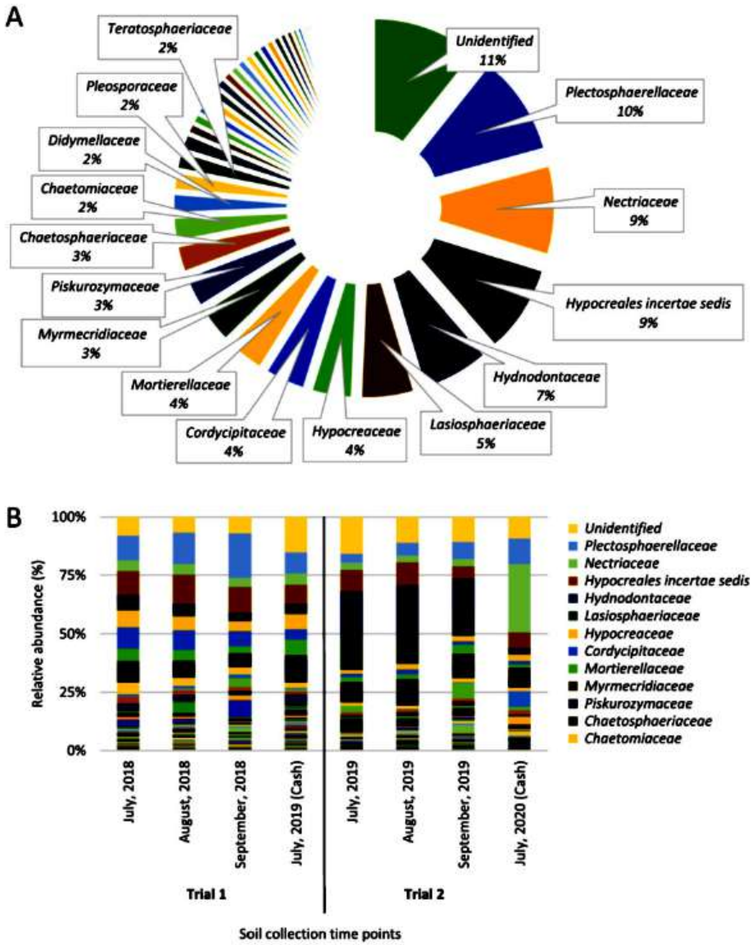

Figure 2.55 – Relative abundance of fungal families in soil samples. (A) Pie chart presenting the average relative abundance of fungal families in all soil samples. (B) Stacked bar chart presenting the changes in the relative abundance of fungal families over time in both trials. Soil samples were collected at three time points during the cover crop phase (July, August, and September), after which soil samples were collected in July of the cash crop phase (Aiyer et al., 2022)

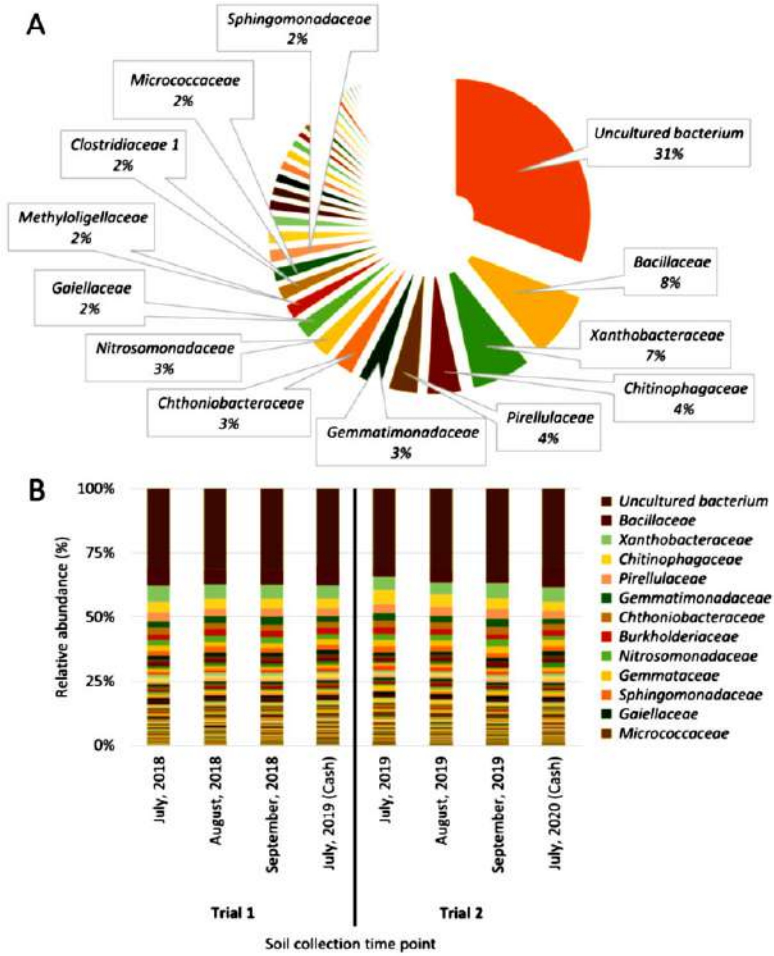

Figure 2.56 – Relative abundance of bacterial families in soil samples. (A) Pie chart presenting the average relative abundance of bacterial families in all the soil samples. (B) Stacked bar chart presenting the changes in the relative abundance of bacterial families over time in both trials. Soil samples were collected at three time points during the cover crop phase (July, August, and September), after which soil samples were collected in July of the cash crop phase (Aiyer et al., 2022)

Fungal alpha diversity was calculated, with a data set rari-fied to 19 729 reads per sample (Fig. 2.57), using Faith's phyloge-netic diversity index. Soil collected from the cash crop phase of the second trial had significantly higher fungal alpha diversity compared with that from the first trial (p value < 0.001). The fungal alpha diversity slowly increased throughout the growing season and the soil collected in the cash crop phase had significantly higher diversity than the soil from the start of the trial. Statistically significant differences in soil fungal alpha diversity between cover crops were observed in the cash crop phase (Table 2). The soil fungal alpha diversity after growing sorghum-sudangrass and Mix-1 was significantly higher than the alpha diversity after Mix-2 (Fig. 2.57A).

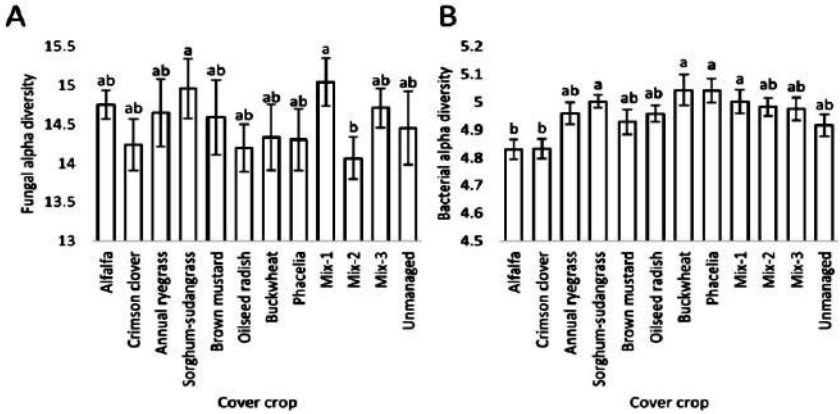

Figure 2.57 – Bar graphs representing average fungal alpha diversity rarified at 19 729 reads (A) and average bacterial alpha diversity rarified at 824 reads (B) for the cash crop phase; n = 12. Different letters indicate statistical significance. Mix-1: buckwheat + crimson clover; Mix-2: phacelia + brown mustard; and Mix-3: buckwheat + crimson clover + brown mustard. Connecting letters for fungal alpha diversity were determined using the SHASH-transformed data set. Error bars indicate standard error (Aiyer et al., 2022)

Bacterial alpha diversity was calculated with the data set rarified to 824 reads per sample (Fig. 2.57A). Similarly to fungal alpha diversity, bacterial alpha diversity also gradually increased over time, with the soil collected from the cash crop phase having significantly higher alpha diversity compared with the previous year. The choice of cover crops significantly influenced the soil bacterial alpha diversity in the cash crop phase. The soil after growing alfalfa and crimson clover had the lowest overall bacterial alpha diversity, while the soil after growing buckwheat, phacelia, sorghum-sudangrass and Mix-1 had significantly higher bacterial alpha diversity (Fig. 2.57 B).

Beta diversity analysis, using weighted UniFrac distance matrices, indicated that soil fungal communities became increasingly dissimilar between cover crops as the growing season progressed in both trials. By September, the soil fungal community composition was significantly affected by the cover crop and stayed different by cover crop in the subsequent year. Fungal community compositions between Mix-1 and Mix-3 soils were conserved in both trials. There were no significant differences in the soil fungal community composition between oilseed radish and phacelia soils in either trial. However, the soil fungal community composition after growing oilseed radish and phacelia was significantly dissimilar from that for every other crop in the first trial. In the second trial, the fungal community compositions associated with oilseed radish and phacelia soils were only dissimilar from those of alfalfa and sorghum-sudangrass soils. The fungal community composition associated with oilseed radish soil was also dissimilar from that of Mix-2 soil in the second trial. In the first trial, the fungal community in Mix-2 soil, which was composed of phacelia and brown mustard, was more similar in composition to that of brown mustard soil compared with that of phacelia soil in both the cover crop and cash crop phases. This trend was the same in the cover crop phase of the second trial, but it was the opposite in the cash crop phase.

The bacterial community composition was significantly affected by the cover crop choice in the cash crop phase the following growing season in both trials. In the first trial, the bacterial community composition associated with annual ryegrass soil was significantly different from that of every other cover crop soil, and the bacterial community associated with alfalfa soil was significantly dissimilar to that of the soils of all the other cover crops except crimson clover. However, in the second trial, the bacterial community composition associated with annual ryegrass soil was only significantly different from that of unmanaged soil, while the community composition associated with alfalfa soil was significantly dissimilar from those of phacelia, oilseed radish, and sorghum-sudangrass soils. Like the fungal community composition, the bacterial community compositions associated with buckwheat, Mix-1, and Mix-3 soils were highly conserved in both trials. In both trials, the bacterial community composition associated with unmanaged soil was significantly dissimilar to those associated with alfalfa, crimson clover, annual ryegrass, sorghum-sudangrass, phacelia, and Mix-3 soils.

FUNGuild was used to taxonomically parse fungal OTUs into groups corresponding to their predicted ecosystem functions. A total of 950 fungal OTUs were classified into one or more of the three functional trophic groups in FUNGuild: 517 OTUs were classified as pathotrophs, 378 OTUs were classified as saprotrophs, and 55 OTUs were classified as symbiotrophs. Fungal OTUs were also subdivided into guilds All three fungal trophic groups were significantly affected by the choice of cover crop in the cash crop season of both trials). Of the 599 OTUs that were found to be differentially abundant by cover crop, 204 were identified as pathotrophs using genus-level classification in FUN-Guild (Figure 2.58 A). These OTUs included several well-known plant pathogens such as Fusarium spp. (Link), Septoria spp. (Desm.), Bipolaris spp. (Shoemaker), Diaporthe spp. (Nitschke), Rhizoc-tonia spp. (Kühn), and Colletotrichum spp. (Corda). The two most abundant Fusarium OTUs were differentially affected by cover crops. However, the two OTUs were both higher in alfalfa soil and lower in crimson clover, brown mustard, oilseed radish, and Mix-2 soils, compared with the un-managed soil (Figure 2.58A). Except for oilseed radish soil, where one OTU was higher in abundance compared with the un-managed soil, both Septoria OTUs were lower in all the cover crop soils than in the unmanaged soil.

Insect pathogenic fungi and fungal biocontrol agents Is-aria spp. ((Berk.) Lloyd), Metarhizium spp. (Sorokin), Beau-varia spp. (Vuil.), Clonostachys spp. (Corda), and Trichoderma spp. (Pers.) were also classified as

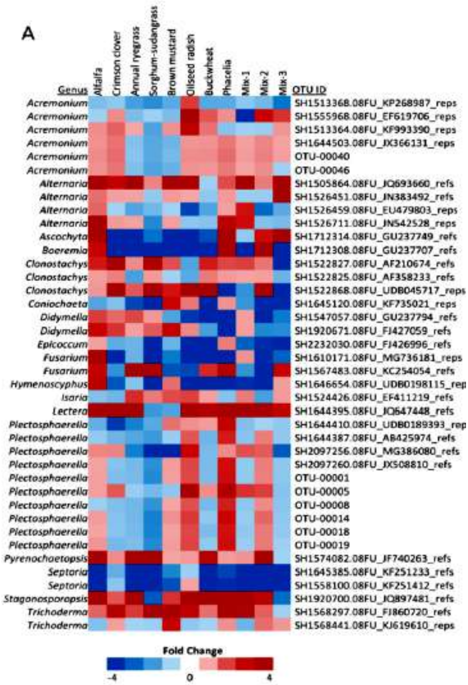

Figure 2.58 A – Differences in abundance of fungal OTUs classified as pathotrophs (A), symbiotrophs (B), and saprotrophs (C) present in the cash crop phase; n = 12. The heatmaps present fold change comparisons of the top 40 most abundant fungal pathotrophs and saprotrophs and the most abundant symbiotrophs found to be significantly different by cover crop. The relative abundance of fungal OTUs in soil from each cover crop was normalized against that of unmanaged soil (Aiyer et al., 2022)

pathotrophs (File S1a). Three Clonostachys OTUs, two Trichoderma OTUs, and one Is-aria OTU were among the top 40 most abundant pathotrophs (Fig. 2.58 A). Clonostachys OTUs were more abundant in alfalfa, crimson clover, sorghum-sudangrass, buckwheat, and Mix-2 soils compared with unmanaged soil, whereas they were less abundant or variable in all the other cover crop soils. Trichoderma OTUs were consistently more abundant in brown mustard, phacelia, and Mix-2 soils compared with unmanaged soil. Isaria spp. were less abundant in alfalfa, crimson clover, phacelia, and Mix-2 soils, and more abundant in all the other cover crop soils, compared with unmanaged soil (Fig. 2.58A). A total of 33 OTUs, which were differentially abundant by cover crop, were classified as symbiotrophs, including several known arbuscular mycorrhizal fungi such as Funneliformis spp. (Walker and SchüEler), Glomus spp. (Tul. and Tul.), and Paraglomus spp. (Blaszk.) (Figure 2.58 B–C). Except for buckwheat soil, most Funneliformis OTUs were more abundant in all the cover crop soils compared with unmanaged soil.

Of 10 799 bacterial OTUs, only 188 OTUs were differentially abundant by cover crop ($a < 0.05$), with fold change comparisons between cover crop soils and unmanaged soils presented in File S1b. These included large bacterial genera such as Bacillus and Pseudomonas, as well as several unidentified taxa. Bradyrhizobium spp., which are known for their role in nitrogen fixation and commonly associated with legume crops, were not significantly different by cover crop. Meanwhile, three OTUs in the genus Pantoea, which includes several plant pathogenic species, were differentially abundant by cover crop, positively associated with alfalfa and Mix-1 soils. To better understand the bacterial community response to the choice of cover crop, bacterial OTUs were parsed into functional groups using FAPROTAX.

A total of 3195 bacterial OTUs were classified into 59 functional groups using the FAPROTAX package on Python. Cover crop effects on most bacterial functional groups in the cash crop phase significantly differed between the two trials, apart from methanol oxidation, methylotrophy, manganese oxidation, and hydrocarbon degradation. The choice of cover crop significantly affected the abundance of bacteria involved in methanol oxidation, methylotrophy, ammonia oxidation, nitrification, sulfate respiration, cellulolysis, manganese oxidation, pho-totrophy, and chemoheterotrophy in the cash crop phase. Bacteria involved in methylotrophy and methanol oxidation were more abundant after growing alfalfa and lowest after growing annual ryegrass. Cellulolytic bacteria were also most abundant after alfalfa, but least abundant after oilseed radish. Chemoheterotrophic bacteria were found in significantly higher

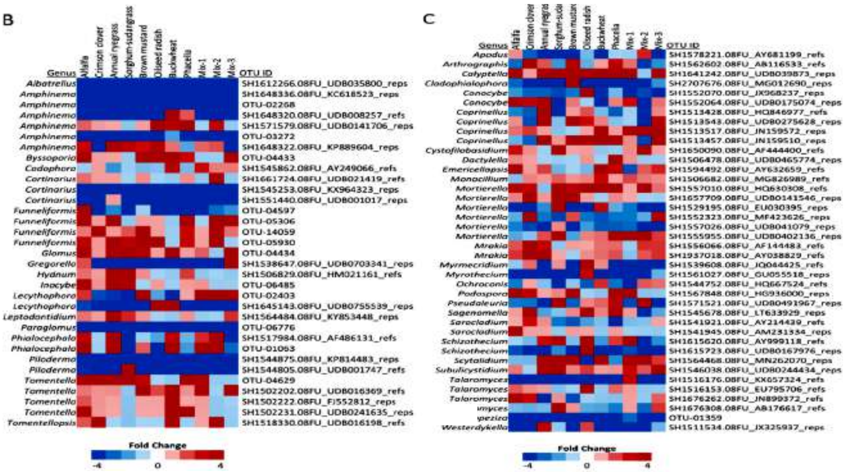

Figure 2.58 B–C – Differences in abundance of fungal OTUs classified as pathotrophs (A), symbiotrophs (B), and saprotrophs (C) present in the cash crop phase; n = 12. The heatmaps present fold change comparisons of the top 40 most abundant fungal pathotrophs and saprotrophs and the most abundant symbiotrophs found to be significantly different by cover crop. The relative abundance of fungal OTUs in soil from each cover crop was normalized against that of unmanaged soil (Aiyer et al., 2022)

abundance in soil collected after alfalfa compared with unmanaged soil. Bacteria involved in ammonia oxidation and nitrification were found in the highest abundance after buckwheat and lowest after Mix-3. Bacteria with the capacity to respire sulfate were more abundant in soil collected after brown mustard, and less abundant after phacelia. Bacteria with the capacity to oxidize manganese were more abundant after Mix-2 and less abundant after annual ryegrass. Genus-level taxonomic identification is listed on the left, with the corresponding OTU reference ID listed on the right. Mix-1: buckwheat + crimson clover; Mix-2: phacelia + brown mustard; and Mix-3: buckwheat + crimson clover + brown mustard.

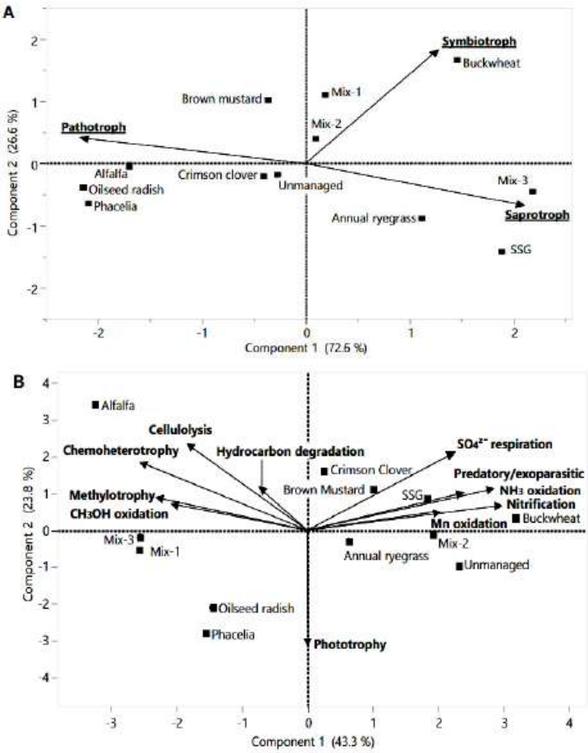

Figure 2.59 A–C – Principal component analysis (PCA) biplots. Principal components 1 and 2 were produced from the least-squares means table and represent the bacterial functional (bolded) and fungal trophic (bold underlined) group relationship with cover crop groups. The trophic group relationship is based on the data collected in the cash crop phase; n = 12. SSG: sorghum-sudangrass; Mix-1: buckwheat + crimson clover; Mix-2: phacelia + brown mustard; and Mix-3: buckwheat + crimson clover + brown mustard. (A) PCA biplot with fungal trophic groups (bolded and underlined) compared with different cover crops. (B) PCA biplot with bacterial functional groups (bolded) compared with different cover crops. (C) Combined PCA biplot with both bacterial and fungal groups in comparison with different cover crops (Aiyer et al., 2022)

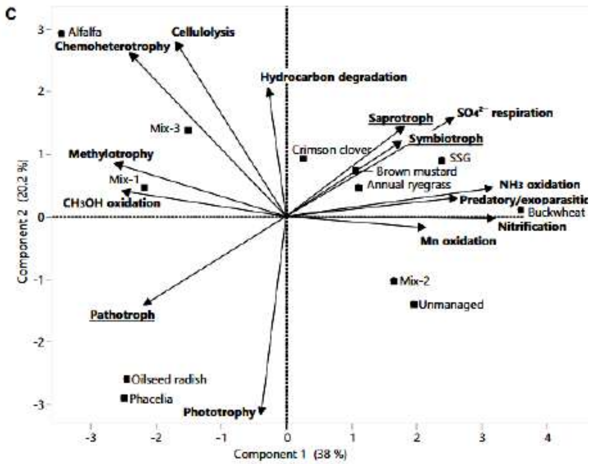

Figure 2.59 A–C (end)

The results from study of Aiyer et al. (2022) indicated that choice of cover crop has a significant influence on soil microbial community composition. The cover crop's influence on the soil microbial communities was found to carry over to the soil in the subsequent year, where it could potentially influence plant health. Choice of cover crop is important as it can affect soil health by manipulating the fungal community composition. The high proportion of plant pathotrophic fungi observed after growing oilseed radish, phacelia, and alfalfa may be an indication of a higher pathogen load, which could lead to increased root disease pressure in subsequently planted crops. Alternatively, the choice of sorghum-sudangrass as the cover crop may lead to disease-suppressive soils and buckwheat to pest-suppressive soils. These results verified the hypothesis regarding beta diversity, as well as functional and trophic group analysis. However, we hypothesized that cover crops would not affect the soil fungal and bacterial alpha diversity in a single growing season, but the results did not support this. This shows that the choice of cover crop has a profound influence on the soil microbiome in a single growing season, thereby influencing soil health.

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CHAPTER 3. OILSEED RADISH IN THE SYSTEM OF MULTI-SERVICE COVER CROP (MSCC) FOR REHABILITATION OF DEGRADED SOILS

3.1. Assessment of oilseed radish potential according to multi-service cover crop (MSCC) criteria

Modern processes of biologization of farming systems through diversification of classical approaches to crop rotation design and their saturation with intermediate crops are aimed at both preventing the degradation of agricultural land and realizing the goals of a significant reduction of anthropogenic impact on the environment (Waha et al., 2020). Usually, the use of intermediate crops in the basic links of crop rotations is considered from many perspectives, from optimizing organic fertilization to reducing the negative status of repeated crops, and in the complex of agroecological approaches guarantees a number of significant benefits that have a long-term positive effect on the overall ecological and productive potential of the soil (Couëdel et al., 2019; Dzvene et al., 2023). In the complex of the identified positive effects of intermediate crops, the paradigm of multi-service cover crop (MSCC) was formed, which is becoming more and more popular every year and gaining importance from the point of view of the system's ability to control negative soil degradation processes and agrochemical and biological transformations in it caused by the intensification of the impact of anthropogenic technological solutions (Justes & Richard, 2017). The very concept of MSCC from the beginning of its design envisaged the cultivation of specially selected crops capable of forming the appropriate biomass in a short period before sowing the main crop in different calendar terms for its green manure use or as a cover crop to control erosion and degradation processes (Couëdel et al., 2019; Lucadamo et al., 2022; Scavo et al., 2022). In the recent period, due to the actualization of such areas as greening and biologization of fertilizers, the development of green bioenergy, the MSCC list also includes the possibility of fodder and bioenergy use of relevant crops (Lavergne et al., 2021). A significant share in the MSCC system is played by the aspects of using intermediate crops to prevent the deficit of organic matter that enters the soil under different fertilization options, reduce the rate of its mineralization and optimize the accumulation of organic carbon (Lei et al., 2022; Lee et al., 2023). Green manure is considered from an ecological point of view as the most rational approach to balanced plant nutrition and guarantees appropriate optimized levels of macro and microelements recycling in assessing their balance in the use-return ratio (Wittwer et al., 2020; Guinet et al., 2023). It is important to investigate the potential of using varietal green manure under variant technological and calendar-term use against the background of widespread involvement of by-products left after harvesting the main crop (Couëdel et al., 2019; Boselli et al., 2020; Kenjaev & Davronova, 2023). This approach is in line with the defined strategy of the green course and adaptive soil conservation in view of the dynamic processes of soil degradation (dehumidification, over-compaction, loss of agronomically valuable structure and the proportion of moisture-resistant aggregates, and increased greenhouse gas emissions) (Ansari et al., 2022; Israt & Parimal, 2023).

Global trends in soil degradation, reduced availability of classic organic fertilizers, and intensive growth in mineral fertilizer prices against the background of a general rise in the cost of traditional energy resources lead to a constant search for alternatives in the agricultural sector of the economy (Kaletnik et al., 2020, 2020a; Honcharuk et al., 2023, 2023a; Tokarchuk et al., 2023). A widely recognized alternative for the formation of ecologically balanced soil use and soil conservation is the use of intermediate crops for multiple purposes in the scheme of classical crop rotations. These types of plants are used for various purposes: biologization of agrotechnologies, soil profile rehabilitation, source of organic recycling fertilization systems (green manure), source of biomass for fodder and bioenergy use, anti-erosion functions, etc. It should be noted that the market for such crops has a pronounced positive growth dynamics. Thus, the Green Manure Global Market Report 2024 (2023) notes that the green manure market size has grown strongly in recent years. It will grow from \$2.17 billion in 2023 to \$2.33 billion in 2024 at a compound annual growth rate (CAGR) of 7.6%. The green manure market size is expected to see strong growth in the next few years. It will grow to \$3.07 billion in 2028 at a compound annual growth rate (CAGR) of 7.1%. The growth in the forecast period can be attributed to climate change adaptation, soil health awareness, regenerative agriculture practices, consumer demand for sustainable agriculture, integration in precision agriculture, enhanced soil microbial activity, water quality management. Major trends in the forecast period include the integration of different cover crops, no-till and reduced-till farming systems, innovations in cover crops, integration of livestock in cover cropping.

Based on the above approaches, a systematic approach to an integrated bio-organic and ecologically oriented approach to soil use was formulated, taking into account the intensity of modern cultivation technologies. This led to the formation of the concept of multi-service cover crop (MSCC) (Justes & Richard, 2017). This concept involves the search, selection and combination in crop rotation of crops that have certain criteria, the main of which are unpretentiousness to the terms of use with the possibility of cultivation in a wide range of calendar dates, intensity and volume of accumulation of aboveground and underground biomass of a certain biochemical quality, intensity of the process of decomposition of their biomass in the soil and suitability for anaerobic fermentation processes (Couëdel et al, 2019; Lucadamo et al., 2022; Scavo et al., 2022). In this complex, the dominants characteristic of the respective soil and climatic zones are distinguished. Thus, a significant part of the MSCC system is played by the aspects of the use of intermediate crops to prevent the deficit of organic matter that enters the soil under different fertilization options (Boselli et al., 2020; Guinet et al., 2023). The relevance of the use of intermediate crops for green manure in the MSCC system is especially relevant in the context of the growing shortage of classical organic matter in fertilization due to changes in the keeping of farm animals and the transfer of modern livestock complexes to schemes for processing manure waste into biogas (Pan et al., 2021), as well as the transition to minimized and zero tillage technologies (Boselli et al., 2020). The positivity of the MSCC conceptual approach is also considered from the standpoint of an effective source of replenishment of soil organic matter with optimized modes of its subsequent humification and normalization of the positive ratio, taking into account the rate of humus mineralization (accumulation of organic carbon in general) (Lei et al, 2022; Lee et al., 2023) and from the point of view of a positive impact on the complex of soil properties (Couëdel et al., 2019; Chen et al., 2020; Ansari et al., 2022; Israt & Parimal, 2023). It has been noted (Justes & Richard, 2017) that MSCC contributes to the optimization of agro-ecological sustainability of agrocenosis and agro-landscapes in general through the optimized filling of ecological niches of fauna and flora of the territories. It is noted that the selection of potential candidate crops that possess the MSCC principle should be based on the study of basic compliance criteria, which for the optimal candidate are multiple in nature (Couëdel et al., 2019; Singh et al., 2023).

It has been noted that the selection of potential candidate crops that possess the MSCC criterion complex should be based on the study of their terms of use and response to soil and climatic resources without compromising the structure of agricultural production in the territories (Yadav et al., 2021; Pryshliak et al., 2022; Abdulraheem & Tobe, 2022; Honcharuk et al., 2023; Lohosha et al., 2023; Singh et al., 2023; Mazur et al., 2023; Tokarchuk et al., 2023). Considering the above arguments, the purpose of the ten-year research cycle was to find out the bioproductive potential of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) on gray forest soils from the point of view of compliance with MSCC requirements. It has been noted (Tsytsiura, 2019, 2020, 2020a, 2021, 2022; 2023, 2023a-b, 2024) that a number of important issues require scientific generalization, in particular, the level of adaptability to changes in sowing dates, patterns of formation of aboveground and underground biomass, its chemical composition, and the possibility of using both green manure and bioenergy options.

The research was carried out during 2014–2023 at the experimental field of Vinnytsia National Agrarian University (N 49°11′31″, E 28°22′16″.) on Grey and Dark Gray forest soils (Greyi-Luvic Phaeozems (Phaeozems Albic, Dark Gray Podzolic Soils) according to WRB (IUSS, 2015)) Haplic Greyzems according to FAO (IUSS, 2015)) of silty clay loamy texture (sicl) (fluctuations in the content of fractions for the horizon 0–30 cm: sand 12.03–14.32, silt 55.86–57.79 and clay 29.35–30.21). The agrochemical potential of the soil for layer 0–30 cm was determined with the standards for analytical laboratory methods (Sparks et al., 1996) and had the following average indicators for the research period: humus content: 2.68%, easily hydrolyzed nitrogen 81.5 mg kg^{-1} of soil, mobile phosphorus 176.1 mg kg^{-1} of soil, exchangeable potassium 110.8 mg kg^{-1} of soil, pH_{KCl} 5.8, hydrolytic acidity 3.29 mg-equivalent 100 g^{-1} of soil. The soil fertility potential based on the presented agrochemical properties was estimated as average (according to Sanchez et al., 1982).

The variety of oilseed radish ‘Zhuravka’ was used. Sowing was carried out on an unfertilized background with a seeding rate of 2.5 million seeds ha^{-1} using the conventional row method (row spacing of 15 cm). This sowing option corresponded to the variant of fodder–green manure use of oilseed radish (Tsytsiura, 2020). Two systems of using oilseed radish as an intermediate crop for multiple purposes in the recommended MSCC system in the study area were investigated:

I. System of early spring sowing after intermediate cultivation in the format of cultivation to a depth of 8–10 cm with leveling (first-second decade of April) against the background of autumn plowing at 20–22 cm at the date of phenological achievement of the optimal phase of multicomponent use of oilseed radish biomass (flowering stage (BBCH 64–67) in the second-third decade of June.

II. The system of intermediate (summer) use for sowing immediately after harvesting the predecessor with intermediate combined tillage (flat cutter + rotary loosening with leveling) to a depth of 12–14 cm in the second or third decade of July at the date of phenological achievement of the optimal phase of multicomponent use of oilseed radish biomass (flowering stage (BBCH 64–67) in the second or third decade of October. The sowing date of the first variant was determined at the early stage of physical ripeness of the soil.

For the second variant, the soil moisture indicator was used based on the date of the nearest precipitation with an intensity of at least 5 mm (according to the recommendations of Florentín et al. (2010)). The optimality of the phase of leaf mass use was determined taking into account the combination of maximum individual plant productivity and relevant quality indicators and corresponds to the recommended variant of biofumigant and green manure use of oilseed radish under conditions of unstable moisture in different soil zones against the background of general recommendations for the phases of cover crops use according to Alonso-Ayuso et al. (2014) and Duff et al. (2020).

A generalized assessment of the hydrothermal regimes of the oilseed radish vegetation period within the years of research is presented in Table 3.1. According to the general classification of the hydrothermal regime of the territories (Latief et al. (2017)), the study period was characterized as conditions of unstable moisture. Taking into account the optimal parameters for the growth processes of oilseed radish plants according to our previous long-term estimates (Tsytsiura, 2020) and the grouping classification by

De Martonne Aridity Index (IDM) and Vysotsky-Ivanov humidification coefficient (K_h), the years of research were placed in the following order of increasing favorability of growth processes for the conditions of spring sowing: 2017–2015–2016–2018–2021–2022–2023–2014–2020–2019. For the conditions of the summer sowing period, a similar series was as follows: 2015–2021–2019–2016–2023–2014–2020–2018–2017–2022.

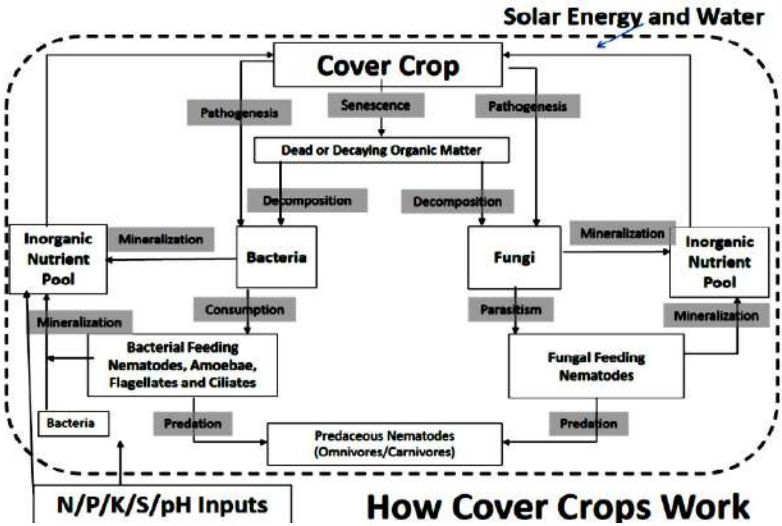
The indicators of variation statistics were determined using the generally accepted calculation method in the statistical software Statistica 10 (StatSoft – Dell Software Company, USA) and Past 4.13 software (Øyvind Hammer, Norway). For statistical evaluation of the obtained average values were used arithmetic mean ($\bar{x}$), standard deviation (SD) and coefficient of variation (CV). Moreover, a Spearman correlation test was used for a statistical level of $p < 0.05^{*}$ and $p < 0.01^{**}$.

The data obtained were analyzed using the analysis of ANOVA (Wong, 2018). Tukey HSD Test in R (version R statistic i386 3.5.3) on the 95% family-wise confidence level were used.

To statistically assess the correlation in accordance with Snecdecor & Cochran (1991) was used the coefficient of determination (R^2) and adjusted coefficient of determination (R^2_{adj}). The Chaddock scale (1925) was used to estimate R^2 (R^2 of 0.1–0.3 indicated a weak relationship; 0.3–0.5 moderate; 0.5–0.7 significant; 0.7–0.9 high; 0.9–0.99 very high).

Both in spring (Table 3.2) and summer sowing (Table 3.3), oilseed radish showed a sensitive wide range of responses to changes in hydrothermal moisture conditions. This influence was realized through a significant difference and variability of biomass of both aboveground and underground parts of plants and the corresponding accompanying ratios. The highest level of aboveground biomass productivity on average during the study period was determined at the spring sowing date of 24.04 t ha^{-1} with a level of interannual variation of 30.55%.

For unstable moisture conditions, it has been established (Ramirez-Garcia et al. 2014; Ugrenović et al, 2019; Safaei et al. 2022; Ţiţei, 2022) the yield of aboveground biomass of such crops as white mustard, spring rape, *Tillage radish (Daikon radish)* in the range of 12–27 t ha^{-1}, winter rape (taking into account biomass in the early summer period) in the range of 25–60 t ha^{-1}. The formed underground (root) biomass for the same group of crops was 5–15 t ha^{-1} and 12–25 t ha^{-1}.



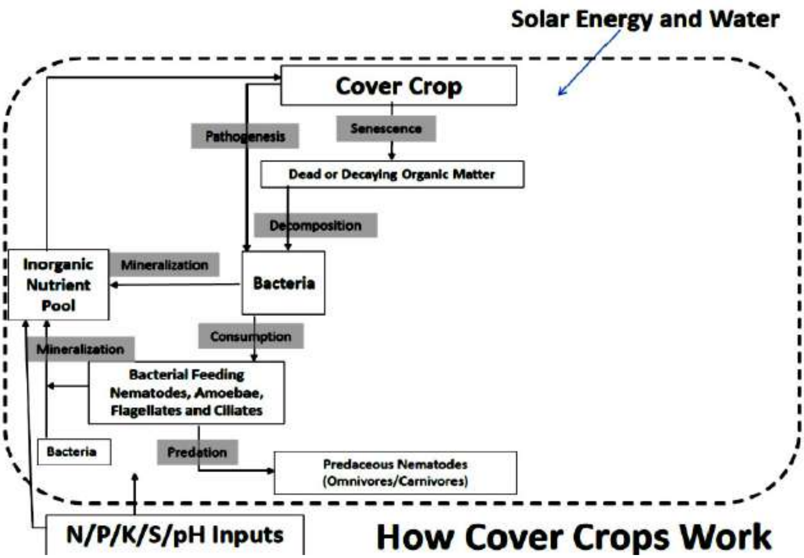


Figure 3.1 – How cover crops work (Warner et al., 2017)

Table 3.1

Estimation of the values of hydrothermal regimes of the period of active vegetation of oilseed radish for the variant of spring and summer sowing, 2014–2023

Year	Precipitation, mm (IV–VI)	*t_{aver}, °C (IV–VI)	Months of the growing season								
			IV			V			VI		
			НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$	ГТК	I_{DM}	$К_h$
Spring sowing											
2014	339.6	13.84	0.725	45.7	1.18	3.928	88.9	2.11	1.545	34.8	0.83
2015	142.3	14.36	0.645	37.3	0.78	0.917	20.6	0.41	0.715	16.9	0.27
2016	193.4	15.06	0.296	21.6	0.44	0.489	40.4	0.99	1.265	29.9	0.75
2017	125.1	14.07	3.919	39.2	0.75	0.777	16.8	0.34	0.504	11.9	0.22
2018	170.8	16.38	0.290	10.8	0.19	0.308	7.2	0.12	4.404	103.7	2.31
2019	398.5	15.39	0.565	33.5	0.72	4.902	111.0	3.29	1.682	41.4	0.96
2020	343.8	13.67	0.091	36.4	0.50	5.327	106.4	3.18	1.548	37.3	0.89
2021	282.8	13.26	0.233	38.8	0.96	3.125	66.7	1.64	1.679	39.8	1.00
2022	242.1	14.30	0.563	57.4	2.33	1.430	31.3	0.79	1.496	36.1	0.85
2023	239.8	14.18	1.543	91.5	3.33	0.085	1.9	0.04	1.640	38.9	0.87

Year	Precipitation, mm (VII–X)	*t_{aver}, °C (VII-X)	Months of the growing season												*t_{aver}, °C	Precipitation amount mm**
			VII			VIII			IX			X				
			НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$		
Summer sowing																
2014	250.8	15.4	1.312	32.7	0.77	1.049	26.0	0.51	1.252	25.7	0.56	1.770	35.8	0.93	–	–
2015	160.8	16.6	0.321	8.1	0.14	0.124	3.1	0.05	1.184	26.8	0.63	3.039	49.4	1.25	0.2	245.5
2016	212.7	15.6	1.056	26.5	0.55	0.898	22.0	0.43	0.014	2.5	0.05	0.548	63.4	2.45	9.5	256.1
2017	318.0	16.0	1.524	37.5	0.72	0.819	20.7	0.38	3.100	61.2	1.57	1.065	30.0	1.26	-0.6	325.7
2018	273.4	16.4	2.158	53.4	1.63	0.585	14.6	0.30	1.378	27.2	0.71	0.873	27.6	0.95	-0.4	323.7
2019	161.7	16.0	1.013	24.4	0.56	0.237	5.9	0.11	0.994	20.7	0.42	0.383	27.4	0.93	0.0	271.0
2020	245.4	17.6	0.589	14.7	0.31	0.527	13.2	0.22	0.859	27.5	0.54	2.544	60.6	3.05	2.9	200.5
2021	176.9	15.4	0.782	20.1	0.45	1.459	35.7	0.91	0.705	17.6	0.51	0.000	1.7	0.04	-0.3	356.1
2022	436.6	16.0	0.900	22.4	0.58	1.712	43.1	1.06	4.960	98.1	2.60	3.167	51.4	1.50	1.2 2.2	216.9 278.0
2023	247.1	18.3	1.414	35.8	0.82	0.652	16.9	0.36	1.015	23.4	0.63	1.025	29.9	0.93	–	–

* – the average daily average temperature (°C) and ** – the amount of precipitation (mm) for the period November of the previous year – March of the following year.

Table 3.2

Indicators of bioproductivity of oilseed radish in spring sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Basic and derived indicators of bioproductivity	Year of observation										*$LSD_{0.5}$
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	
Leaf and stem biomass yield, t ha^{-1}	33.49	20.11	21.29	15.22	13.89	35.75	30.88	24.12	21.18	24.48	1.39
Dry matter content of leaf and stem biomass, %	12.23	14.12	14.19	13.75	15.11	11.27	12.73	11.81	13.28	13.09	0.64
Leaf and stem biomass yield in dry matter, t ha^{-1}	4.10	2.84	3.02	2.09	2.10	4.03	3.93	2.85	2.81	3.20	0.24**
Root biomass yield, t ha^{-1}	13.28	7.88	6.22	4.47	3.39	14.85	13.02	9.57	7.44	6.87	1.15
Dry matter content in the biomass of root residues, %	20.42	23.12	21.73	22.84	23.95	20.68	19.84	19.09	21.47	21.11	0.88
Root biomass yield in dry matter, t ha^{-1}	2.71	1.82	1.35	1.02	0.81	3.07	2.58	1.83	1.60	1.45	0.26**
Total biomass produced (roots + aboveground biomass), t ha^{-1}	46.77	27.99	27.51	19.69	17.28	50.6	43.9	33.69	28.62	31.35	1.99
Total biomass produced (roots + aboveground part) in dry matter, t ha^{-1}	6.81	4.66	4.37	3.11	2.91	7.10	6.51	4.68	4.41	4.65	0.36
Root system productivity factor in raw weight	2.52	2.55	3.42	3.40	4.10	2.41	2.37	2.52	2.85	3.56	0,62
Root system productivity factor in dry matter	1.51	1.56	2.24	2.05	2.59	1.31	1.52	1.56	1.76	2.21	0.38
Share of root biomass in the crude total biomass of plants, %	28.39	28.15	22.61	22.70	19.62	29.35	29.66	28.41	26.00	21.91	1.05
Share of root biomass in dry total plant biomass, %	39.83	39.08	30.91	32.79	27.89	43.25	39.65	39.07	36.22	31.16	0.56
Leafiness of plants, %	43.91	40.84	41.27	38.22	40.81	48.78	46.77	38.29	43.92	43.26	2.89
Share of stem, %	47.77	49.81	45.08	47.44	46.87	42.89	42.42	51.68	44.72	46.31	2.56
Share of the generative part, %	8.32	9.35	13.65	14.34	12.32	7.33	9.81	10.03	11.36	10.43	0.98
Survival rate of plants, %	90.24	86.17	85.74	83.51	81.23	93.21	90.78	88.09	87.28	87.92	4.44
IVC	1.310	0.807	0.781	0.623	0.572	1.443	1.293	0.992	0.850	1.015	0.06

*LSD_{05} for values in % in the expression of a fraction of the numerical value of the indicator according to Snecdecor & Cochran (1991); ** in combinatorial comparison of crude weight and dry matter content by repetitions according to Snecdecor & Cochran (1991).

Table 3.3

Indicators of bioproductivity oilseed radish in summer sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Basic and derived indicators of bioproductivity	Year of observation										*$LSD_{0.5}$
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	
Leaf and stem biomass yield, t ha^{-1}	22.21	9.49	21.05	23.79	23.12	10.11	11.29	16.22	24.77	21.39	1.29
Dry matter content of leaf and stem biomass, %	15.17	17.52	15.97	14.27	14.91	17.15	16.08	16.83	13.43	15.75	1.11
Leaf and stem biomass yield in dry matter, t ha^{-1}	3.37	1.66	3.36	3.39	3.45	1.73	1.82	2.73	3.33	3.37	0.27**
Root biomass yield, t ha^{-1}	6.59	1.39	5.77	7.21	5.52	3.58	3.09	6.49	8.03	7.33	0.60
Dry matter content in the biomass of root residues, %	22.17	25.18	23.12	21.08	23.29	20.15	22.68	23.32	21.91	23.52	1.08
Root biomass yield in dry matter, t ha^{-1}	1.46	0.35	1.33	1.52	1.29	0.72	0.70	1.51	1.76	1.72	0.13**
Total biomass produced (roots + aboveground biomass), t ha^{-1}	28.8	10.88	26.82	31	28.64	13.69	14.38	22.71	32.8	28.72	2.19
Total biomass produced (roots + aboveground part) in dry matter, t ha^{-1}	4.83	2.01	4.70	4.91	4.73	2.46	2.52	4.24	5.09	5.09	0.27
Root system productivity factor in raw weight	3.37	6.83	3.65	3.30	4.19	2.82	3.65	2.50	3.08	2.92	0,48
Root system productivity factor in dry matter	2.31	4.75	2.52	2.23	2.68	2.40	2.59	1.80	1.89	1.95	0.32
Share of root biomass in the crude total biomass of plants, %	29.67	14.65	27.41	30.31	23.88	35.41	27.37	40.01	32.42	34.27	1.67
Share of root biomass in dry total plant biomass, %	43.36	21.05	39.68	44.77	37.29	41.60	38.60	55.44	52.89	51.17	3.56
Leafiness of plants, %	35.41	37.22	35.79	36.77	35.56	33.51	34.15	30.29	38.37	33.11	2.72
Share of stem, %	52.28	57.26	51.89	47.25	45.81	55.18	48.53	54.27	41.88	49.27	2.38
Share of the generative part, %	12.31	5.52	12.32	15.98	18.63	11.31	17.32	15.44	19.75	17.62	1.36
Survival rate of plants, %	80.28	70.29	80.17	81.08	81.52	71.17	70.14	77.37	82.31	78.79	3.09
IVC	0.780	0.334	0.763	0.971	0.876	0.333	0.479	0.481	1.027	0.781	0.08

*LSD_{05} for values in % in the expression of a fraction of the numerical value of the indicator according to Snecdecor & Cochran (1991); ** in combinatorial comparison of crude weight and dry matter content by repetitions according to Snecdecor & Cochran (1991).

Based on these results, oilseed radish can be attributed to highly productive crops with developed adaptive mechanisms of plant biomass formation. Such statements are also consistent with the results of the assessment of the dynamics of oilseed radish aboveground biomass formation with a focus on phenotypic resources of the growing season (Figure 3.2, Table 3.4). It should be noted that the models widely used in the practice of mathematical analysis of the formation of aboveground plant mass, such as the Gompertz model, Logistic model, Linear-exponential model (Tjørve & Tjørve, 2017), according to the results of statistical evaluation for adequacy, were ineffective for oilseed radish with a moderate closeness of dependence (R2<0.5) and were not included in Table 3.4. This indicates a certain species specificity of the formation of the indicator characteristic of cruciferous crops and is consistent with the findings of Ramirez-Garcia et al. (2014), who found, for example, that white mustard among the 5 species of cover crops (cereals, cruciferous and legumes) studied by them had the lowest statistical estimates of R^2 in the system of modeling its biomass growth in accordance with the above three models. Similar conclusions were reported by Tribouillois et al. (2016) and Snapp et al. (2005).

According to the correlation and statistical assessment of the curves of dynamic growth of aboveground biomass, with the dominance of power and exponential dependencies (Table 3.4), the Harris Model and Quadratic Fit for both sowing dates under the determination of the relationship (d_{xy}) were found in the range of 82.2–88.7% and 69.4–79.7%. Certain features of aboveground biomass formation have also been established. These are slow rates of its formation in the interval up to 1000 °C Day after sowing with intensive growth from the date of 1000 °C Day for spring and 1300 °C Day for summer sowing. That is, oilseed radish is characterized by a hyperbolic nature of biomass growth with the maximum intensity in the second half of the growing season. At the same time, the intensity of these processes in the spring sowing period was significantly more uniform than in the summer. This is proved by the level of determination of the dependence of the curve formation at the spring sowing date in such models as 'Exsponential Association' (d_{xy} = 78.0%) and ‘MMF Model’ (d_{xy} = 79.2%). In the case of summer sowing for these models, both the closeness of the relationship and the level of its adequate description by these models were significantly lower (47.4% and 65.7%, respectively).

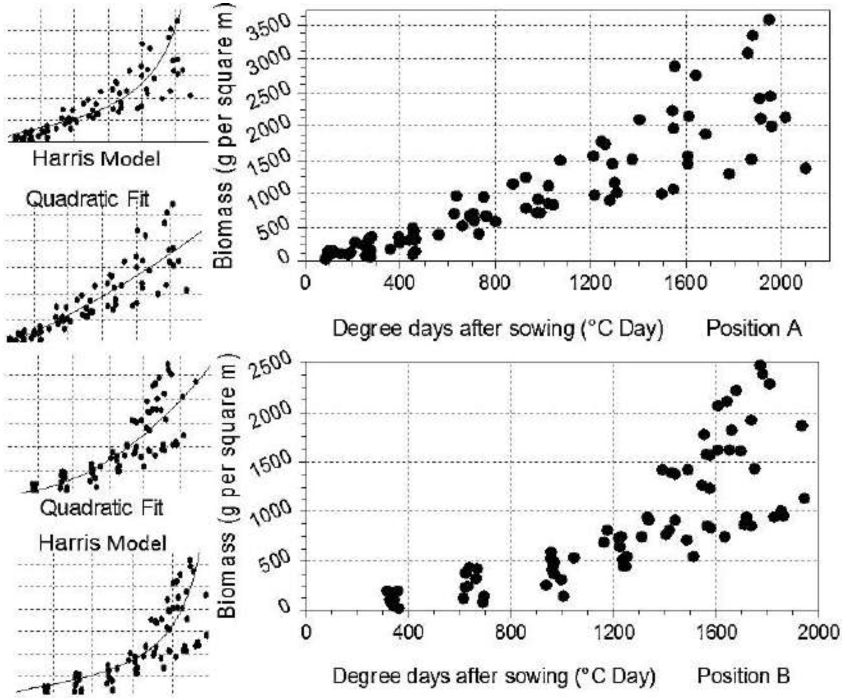


Figure 3.2 – Dynamics of formation of aboveground biomass of oilseed radish plants at different sowing dates in the total data set for 2014–2023 (g m^{-2}) (Position A – spring, position B – summer sowing dates) (based on the results of the author's own research)

For the same reasons, the closeness of the relationship in the 'Quadratic Fit' model in terms of R^2 for the spring sowing period was 14.8% higher than for the summer sowing period. As a result, taking into account the level of average daily temperatures (Table 3.4), an intensive period of growth of aboveground biomass from the stemming phase of oilseed radish plants for the spring sowing period (BBCH 30–32) and from the rosette phase (BBCH 24–26) for the summer sowing period should be expected with a high level of probability. That is, a steady-growing type of aboveground biomass formation was noted in the spring and unevenly growing for the summer sowing period. Taking into account the studies of Toom et al. (2019) and Konuntakiet (2020), the summer sowing period of oilseed radish will have more pronounced critical periods in terms of the need for hydrothermal resources than spring, which will require taking this factor into account when determining the possibility of sowing in summer for areas with unstable moisture or a characteristic deficit of atmospheric moisture against the background of an intensive increase in average daily temperatures. On the other hand, taking into account the analysis of aboveground biomass formation curves for a number of cover crops in the studies of Ramirez-Garcia et al. (2014, 2015), the parameters ‘c’ and ‘d’ in the models in Table 4 should be referred to as ‘weighted mean relative growth’. Its value for different growth models in different types of intermediate-use cover crops ranges from 0.002–1.500 (Ramirez-Garcia et al., 2014; Bhogal et al., 2019; Wallander et al., 2021). The obtained values of this indicator in the presented models for oilseed radish confirmed the generalizations made about the uneven growth dynamics and intensive biomass growth in the second half of the growing season, taking into account the statement of Tjørve & Tjørve (2017) and the value of the parameter ‘c’ for individual applied models for oilseed radish with a dimensionality < 0.001.

According to Thorup-Kristensen & Kirkegaard (2016), the efficiency of multipurpose use of field crops is largely determined by the productivity of their root system, which can be used in different ways from the productivity coefficient to the share of root biomass in the formed plant biomass. According to the obtained indicators of bioproductivity of oilseed radish, the productivity coefficient of the root system in terms of the obtained crude biomass averaged 2.97 (20.33%) for the full period of study in spring and 3.63 (33.69%) in summer sowing. In terms of dry matter equivalent, these figures were 1.83 (22.82%) and 2.51 (33.53%). At the same time, the inverse ratio of root mass to aboveground mass for the spring sowing period was 0.35 in terms of wet weight and 0.57 in terms of dry matter at a level of interannual variation of 18.67–21.24%. For the summer sowing period, these indicators were at the level of 0.30 and 0.43 and 22.98–23.63%, respectively. Taking into account the statements of Thornley (1998) and Bláha (2021), this level of ratio on the one hand indicated the rapid growth rate of oilseed radish plants for both parts of the plants with parity development of aboveground mass and the presence of a sensitive stress response to deteriorating soil conditions in terms of moisture, aeration, etc. At the same time, the inertia of the growth of the aboveground part when the growth of the underground part is stopped has also been proven. This is confirmed by a decrease in the level of interannual variation of the ratio of root biomass to aboveground biomass with a coefficient of 1.88 for spring sowing and 1.54 for summer sowing, based on the studies of Fageria et al (1997) and Williams et al. (2013). This inertia, which determines the preservation of the intensity of growth processes due to the more pronounced stress resistance of the root system (noted in cruciferous species by Ahmad et al. (2012)) allows oilseed radish plants to adapt to possible medium-long periods of aridization and ensure the formation of aboveground plant biomass at the level of 50% of the long-term average in years with low values of the aridity index (I_{DM}) and moisture coefficient (K_h). For example, this is typical for the conditions of 2015 (Table 1) for both sowing dates of oilseed radish and for the conditions of 2017 for the spring sowing date. These processes of reducing the growth rate of oilseed radish plants are predicted to increase with a simultaneous increase in the significance of the deviation from the optimum of both aboveground and underground temperature and humidity conditions. Such conclusions are based on the studies of Williams et al. (2013), Feller et al. (2015), Agathokleous et al. (2019), Kul et al. (2021). At the same time, for oilseed radish, it is possible to have an intensive formation of root biomass at a minimum rate of aboveground biomass formation, which is possible already at a level ratio of the proportion of roots to the proportion of vegetative parts above 0.25 (according to Feller et al. (2015)) and was noted in the studies of Heuermann et al. (2019) on white mustard in a stressful year of vegetation. This is clearly confirmed by visualization of the correlation between underground and aboveground biomass in the total data set for the study period (Figure 3.3).

In particular, a positive numerical value of aboveground biomass was found at a zero value of root biomass, as well as the correspondence of the abscissa step of the graph to 4 units, which corresponds to a similar ordinal step of 15 units for the indicators of the formed crude plant biomass. For the same indicator in dry matter, 2 units of the abscissa of the graph account for 3.5 units of the ordinal position. That is, the strength of the relationship decreases in the case of biomass conversion to dry matter, which is confirmed by a significantly lower value of the correlation coefficient

(15.9% decrease in comparison with crude biomass) and is evidence of a pronounced asynchrony between the dry matter content in the aboveground and underground parts of plant biomass. This difference increases with the change in sowing dates from spring to summer (Table 3.2–3.3).

Table 3.4

Estimation of parameters of models of oilseed radish aboveground biomass formation (y) in the dynamics of Degree days after sowing (°C Day (x)) growth at two sowing dates, 2014–2023 (based on the results of the author's own research)

Model (model equation)	Parameters of the equation				Statistical evaluation of components				
	a	b	c	d	r	R^2	F	df1, df2	*p*
Spring sowing									
Quadratic Fit ($y=a+bx+cx^2$)	-42.35	-0.928	0.000158	–	0.893	0.797	22.012	2.170	*<0.001*
Exsponential Association ($y=a(1-exp^{-bx})$)	3093.9	0.0000237	–	–	0.883	0.780	18.156	2.170	*<0.001*
Logaritmth Fit ($y=a+b\ln x$)	-2071.3	524.7	–	–	0.700	0.490	3.599	2.170	*<0.05*
Harris Model ($y=(a+bx^c)^{-1}$)	0.025	-0.017	0.05	–	0.907	0.822	22.749	2.170	*<0.001*
MMF Model ($y=(ab+cx^d)(b+x^d)^{-1}$)	-91.60	44675.1	23808.5	1.12	0.890	0.792	21.708	2.170	*<0.001*
Summer sowing									
Quadratic Fit ($y=a+bx+cx^2$)	24.17	0.011	0.00048	–	0.833	0.694	14.599	2.170	*<0.001*
Exsponential ($y=a(b-exp^{-cx})$)	2477.0	1238.5	0.0019	–	0.689	0.474	4.188	2.170	*<0.05*
Exsponential Association ($y=a(1-exp^{-bx})$)	2322.3	0.0000287	–	–	0.775	0.600	8.569	2.170	*<0.001*
Logaritmth Fit ($y=a+b\ln x$)	-1768.3	380.7	–	–	0.543	0.295	1.926	2.170	*>0.05*
Harris Model ($y=(a+bx^c)^{-1}$)	0.049	-0.0034	0.05	–	0.942	0.887	23.293	2.170	*<0.001*
MMF Model ($y=(ab+cx^d)(b+x^d)^{-1}$)	-413.39	26215.5	22413.5	1.04	0.811	0.657	11.231	2.170	<0.001

Similar studies by Kemper et al. (2020) showed rapid rooting rates of oilseed radish with the formation of significant root biomass at higher rates of this process with a decrease in sowing rates when using oilseed radish as an intermediate cover or green manure crop with a fluctuation of the share of root biomass in the total phytomass from 18 to 50%. This is fully consistent with the results of our long-term research. The data obtained give grounds to assert that under optimal conditions of soil moisture and nutrition against the background of intensive increase in average daily temperatures and a certain duration of absence of precipitation, oilseed radish is able to maintain high rates of growth processes, which allows it to be used as an intermediate crop in the conditions of hot cycles of periods between the main crops of the crop rotation. This is based on both the high values of the direct and inverse ratio of aboveground and belowground biomass of oilseed radish plants in the experiment and is confirmed by a number of studies on other crops (Bacher et al., 2021; Kou et al., 2022). It should also be noted that the high proportion of root biomass in the total biomass of oilseed radish plants on average over the full cycle of research (25.68% in spring sowing (interannual variation of 14.19%) and 29.54% (23.63%) in summer sowing) indicates a high level of adaptation of oilseed radish to soil nutrition conditions from the point of view of the possibility of obtaining high levels of productivity on soils with low agrochemical potential.

This level of ratio, especially with an increase in the share of root biomass in the total dry biomass of plants by an average of 10.31–13.05% depending on the sowing date, also showed a high probable positive response of oilseed radish plants to additional mineral nutrition through the use of mineral fertilizers and a high intensity of accumulation of basic nutrients in the formed plant biomass. These conclusions are in line with the studies of Redin et al (2018), Lopez et al. (2023). Leafiness of oilseed radish plants, which is considered on the one hand as an indicator of potential overall plant compatibility, and on the other hand is an expression of the value of the crop in terms of soil surface coverage (Bhogal et al., 2019), biomass growth rate and faster rates of mass decomposition in the soil under green manure use (Quintarelli et al., 2022). In general, for optimized green manure options, plants should have a leaf cover of at least 30% (Liu et al., 2020). For a system of possible biogas utilization of biomass, this indicator should be in the range of 20-30%, which creates prerequisites for an optimal C/N ratio of 18-22 and provides sufficient starting levels of biomethane productivity in the first decade of anaerobic biofermentation of fresh, dried or pre-siloed cruciferous biomass (Herrmann et al., 2016; Tsytsiura Y. 2023a).

At the same time, the level of this indicator had significant differences in the spring and summer sowing dates of oilssed radish. Thus, on average, during the ten-year study period, the leaf area of plants was 42.61% (with an interannual variation of 8.03%) in the spring sowing period. In the summer sowing period, this figure was 7.59% lower, with a decrease in interannual variation of 1.35%. The presented data give grounds to assert the difference in the idiotypic structure of oilseed radish plants formation

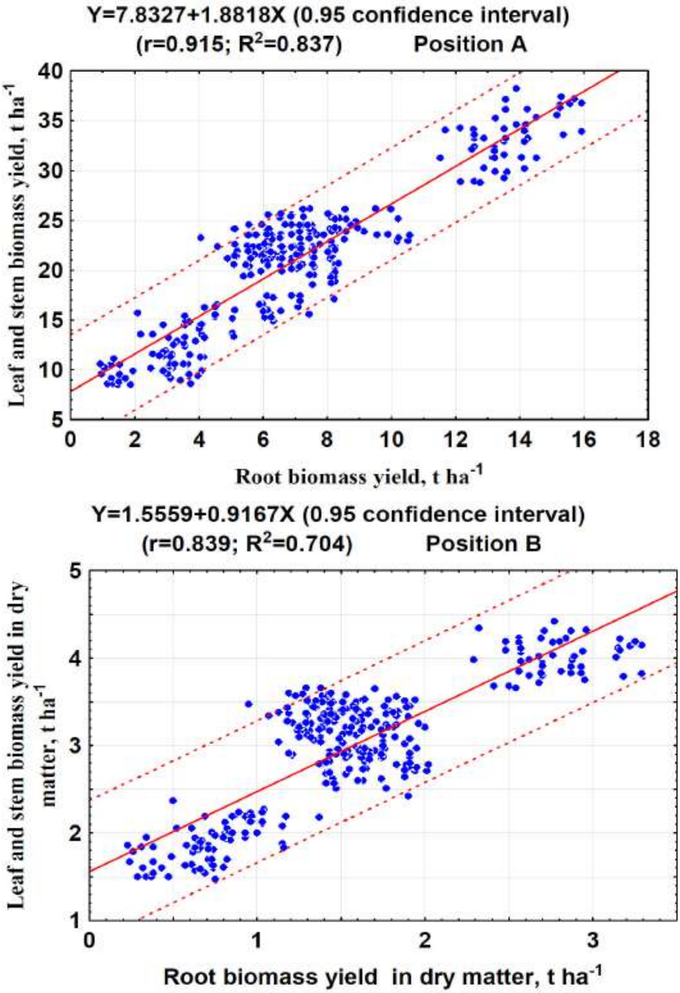


Figure 3.3 – Relationship between aboveground biomass yield and formed root biomass in oilseed radish, 2014-2023 (in a single data system of replication–year–sowing date for *N = 320;* position A – in raw mass, B – in dry matter) (based on the results of the author's own research) (based on the results of the author's own research)

when sowing dates are changed. In this case, the morphogenesis of plants is aimed at increasing the proportion of the stem from 46.50% on average for the variants of spring sowing to 50.36% for the variant of summer sowing. Another positive property of oilseed radish plants was confirmed to be the ability to maintain relatively constant levels of reproductive effort (proportion of the generative part (%)) with changes in sowing dates at the level of 10.69–14.62. This is in line with our previous findings (Tsytsiura, 2019; 2022) regarding the possibility of juvenile flowering of oilseed radish and accelerated growth rates in development during the period of stem formation and the beginning of the formation of the generative part of plants. This property is valuable from the point of view of growth rates under aridization of soil and climatic conditions of vegetation for the selection of a crop as a candidate for a group of intermediate crops in crop rotations of different rotation and the system of their green manure use.

It should be noted the sensitive response of oilseed radish plants to environmental conditions by changing their complex morphogenesis in terms of index vitality coefficient (IVC), which is consistent with our previous studies (Tsytsiura, 2020) and with the findings of Zlobin et al. (2021). This is confirmed by the high values of interannual variation of IVC under stressful growth and development conditions from the traditional spring start of the growing season (30.81%) to the more stressful (summer) one (37.54%).

At the same time, there was an increase in the general depression of plant morphogenesis in comparison of summer and spring terms of oilseed radish use with a growth coefficient of 1.42 in favor of summer terms. This led to the presence of IVC below 0.50 in a number of years with summer (intermediate) use of oilseed radish, which corresponds to the level of intense morphodepression. Under these conditions, the content of dry matter in the leaf and stem biomass of plants naturally increases and an idiotype of plants with higher leafiness is formed with a smaller proportion of the stem and a smaller proportion of the generative part. This character is consistented with the general life strategies of plants described by Zlobin et al. (2021) and differs from such cruciferous crops as white mustard, spring and winter rape. According to Heuermann et al. 2019 and Israt & Parimal (2023), the optimal moisture content of both soil and atmospheric moisture during the period of active growth is determined for mustard, and the period of stress response during summer sowing is quite short, which is determined by the level of vaporization of the leaves themselves and the rapid rate of decline in leafiness under conditions of high average daily temperatures. For spring rape, an intensive decrease in growth processes and the formation of aboveground biomass during sowing in summer against the background of increasing average daily temperatures was noted (Li et al., 2019) with subsequent optimization of growth processes at lower temperatures against the background of increasing precipitation with a shift in the timing of intermediate and green manure use to the autumn period. During the summer sowing period, higher levels of the formed underground biomass (roots) in comparison to the aboveground part of plants were studied (Ugrenović et al., 2019).

Taking into account the value of the survival rate of oilseed radish plants, significant differences in stress were found when using oilsed radish in the spring sowing period under the system of occupied fallow and in the summer period under the variants of intermediate (green manure) culture. Thus, the average survival rate for 10 years of our research (Tables 3.2, 3.3) was 87.42% for spring and 77.31% for summer sowing with interannual variation of 4.03% and 6.31%, respectively. A significantly lower level of variation of this indicator confirmed the useful mechanisms of adaptation of oilseed radish plants described by us in the system of its long-term and varied use.

The above analyzed features of oilseed radish growth processes allowed us to analyze another important indicator, namely 'ground cover' (GC), which is taken into account in the MSCC evaluation criteria in the case of using the crop as a 'cover crop' (integrated in the crop rotation between two cash crops) (Bodner et al., 2010). At the same time, it is noted that the main criterion is the duration of achieving a GC rate of at least 70% for the shortest possible period (Tixiera et al., 2010; Ramírez-García et al., 2015). The long-term evaluation of oilseed radish by GC is shown in Figure 2. For both sowing dates, a power-law exponential dependence was observed, which differs from the classical version of the Gompertz function, which assumes an asymptotic increase to maximum coverage and has the model function given in Bodner et al. (2010). In addition, the actual functional dependence is confirmed by the Chaddock (1925) scale as very close for both sowing dates and has a decline after reaching the peak value. This dynamics differs from the classical plateaued area or a curve with a small growth coefficient. Based on the established patterns of formation of the leaf apparatus of oilseed radish (Tsytsiura, 2020a) associated with a decrease in plant foliage from the beginning of flowering (BBCH 50–52) and intensive growth at the end of flowering (BBCH 68–69).

On 55–75 days after sowing, intensive leaf death was observed in oilseed radish. Based on this, it was found that the maximum soil coverage was observed on the 60th day after sowing in the spring sowing period (with a fluctuation in the range of 71.23–93.67 with an average value for the period of research of 83.69%) and on the 50th day in the summer sowing period (60.27–90.36% and 79.94%, respectively). Based on the study of Werker & Jaggard (1997), it was assumed that the ratio of the coefficients of the equation that most likely describes the mathematical regularity of the formation of the GC index of oilseed radish in the expression of the power $X2c^{-2}$ and $2bxc^{-2}$ for the spring sowing term and bx^{-1} for the summer sowing term (where X is days after sowing) is an indicator of the natural process of leaf death. These coefficients are the result of both the dynamic growth of the curves and the specifics of their decline (Figure 3.4).

It is also worth noting the peculiarities of growth dynamics. For the spring sowing period, the initiation of cover is characterized by the 15th day after sowing, and for the summer – by 20–25 days. At the same time, for the summer sowing period, both more intensive growth and more intensive decline in the dynamics on the dates of accounting were noted, which ultimately affected the final GC index on the 70th day after sowing: on average for the entire study period 73.77% for spring and 50.74% for summer sowing. The level of variability in the array of medium-term data in a number of accounting dates was also significantly different – 22.43% for spring and 29.93% for summer sowing dates. At the same time, for the summer sowing variant, the range of GC values had a pronounced upward trend from the 55th day of accounting (Figure 2, bottom position) to the date of accounting. Thus, with certain similarities in the formation of the GC index, which confirms the above features, the formation of biomass of oilseed radish plants, the intensity of achieving both the peak GC index and the decrease in leafiness is significantly less long in the summer sowing period. This reduces the duration of effective use of oilseed radish in the cover crop format during summer sowing under the regime of unstable moisture to 45–55 days after sowing. For the spring sowing variant, this indicator is prolonged to 70 days. If we analyze the GC index for a number of other cruciferous crops (according to the studies of Florentín et al., 2010;

Bodner et al., 2010; Ramírez-García et al, 2015; Couedel, 2019; Bhogal et al. (2019)), it should be noted that, given the common properties of leafiness reduction from the full flowering to maturation phase, the maximum GC level of more than 90% was achieved under optimal moisture in winter rape when used as a cover crop. For white mustard, spring rape in the system of their intercropping, this indicator in optimal years reached the level of 80–84% on 60–75 days after sowing. However, the duration of the 'cover crop' function in these crops is longer from 65 to 90 days after sowing at a slower rate of leaf decline in the process of physiological leaf death during maturation.

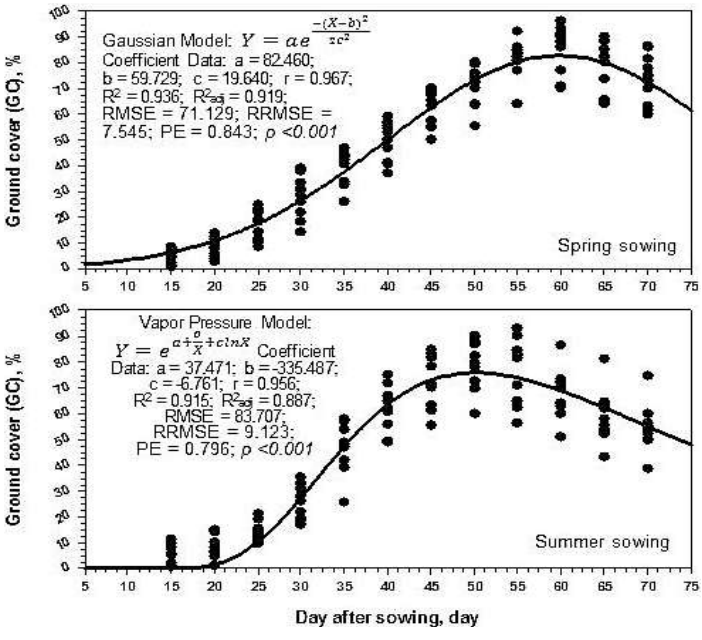


Figure 3.4 – Graphical model with statistical evaluation parameters for the indicator 'Ground cover' (GC) in oilseed radish (vertical marks on the dates of accounting – indicator values in the experimental interval 2014–2023) (based on the results of the author's own research)

The above features of oilseed radish have certain regularities of formation from the point of view of hydrothermal conditions of vegetation, confirmed by the results of correlation analysis (Table 3.4). According to the size of the correlation graph of the first type (Graf G), the formation of both aboveground and underground (root) biomass of oilseed radish plants had the highest total dependence of modular numerical values of correlation coefficients (12.60 and 12.59, respectively), and among the hydrothermal factors of the growing season, this indicator was maximum for hydrometeorological coefficients such as HTC, I_{DM}, K_h (on average >12). Among the parametric factors, the amount of precipitation played a more significant role in the system of formation of the total bioproductivity of plants than the level of average daily temperature (Graf G for the amount of precipitation was 27.4% higher). According to the values of the correlation graph of the second type (Graf G′), the coefficient of determination was 49% for the Aridity Index (I_{DM}), 46.2% for the hydrothermal coefficient (HTC), 47.6% for the humidification coefficient (K_h), 44.9% for the amount of precipitation, 28.1% for the average daily temperature and 13% for the relative humidity. At the same time, the level of correlating certainty for the value of the total formed plant biomass was 49%. Based on this, the determining factor in the formation of the total bioproductivity of oilseed radish plants will be the total moisture supply during their vegetation period due to atmospheric moisture and the processes of changing this indicator in relation to evaporation, temperature dynamics and their growth rates and changes over time. At the same time, a significantly lower dependence on the average daily temperature gives grounds to assert its adaptive resistance to low temperatures and the ability to initiate growth processes in the early and very early stages. In this case, the direction of the dependence established that the level of total biomass of oilseed radish plants with a high level of predicted probability will increase with increasing precipitation (d_{yx}=92.2%), decreasing average daily temperature (d_{yx}=23.0%), increasing relative humidity (d_{yx}=24.0%) and high values of hydrothermal coefficients and ratios (d_{yx}=81.0–88.4%). If we compare the obtained dependencies with the model parameters that were included in the predictive models of biomass formation for such species as spring and winter rape, white mustard in variants of its multiple use (Dorsainvil et al., 2005; Saseendran et al., 2010; Deligios et al., 2013; Jing et al., 2016; Asgari et al., 2021), it should be noted that oilseed radish has certain advantages in terms of climate adaptation indicators.

Table 3.4

Pearson's correlation coefficients of dependence of oilseed radish bioproductivity parameters on hydrothermal parameters of the growing season (for a joint system of matching sowing dates–repetitions–years (*N=160*)) (based on the results of the author's own research)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	-0.40	0.49	0.91	0.96	0.91	0.95	0.95	0.96	-0.76	-0.64	-0.51	0.52	0.59	-0.46	-0.55	0.77	0.72
2		-0.02	-0.71	-0.62	-0.71	-0.44	-0.53	-0.48	0.77	0.54	0.51	-0.54	-0.43	-0.57	0.72	-0.80	0.68
3			0.29	0.37	0.29	0.52	0.36	0.49	-0.43	-0.32	-0.35	0.28	0.55	0.34	0.33	0.53	0.46
4				0.99	1.00	0.87	0.93	0.90	-0.86	-0.73	-0.57	0.61	0.65	-0.07	-0.70	0.86	0.62
5					0.99	0.91	0.96	0.94	-0.85	-0.71	-0.56	0.60	0.65	-0.10	-0.66	0.85	0.84
6						0.87	0.93	0.90	-0.86	-0.73	-0.57	0.61	0.65	-0.07	-0.69	0.86	0.72
7							0.94	0.99	-0.82	-0.57	-0.41	0.40	0.68	0.48	-0.64	0.86	0.76
8								0.97	-0.81	-0.65	-0.63	0.66	0.62	0.54	-0.68	0.83	0.61
9									-0.83	-0.61	-0.49	0.49	0.67	0.63	-0.66	0.86	0.72
10										0.66	0.52	-0.51	-0.62	0.45	0.75	-0.92	-0.40
11											0.62	-0.58	-0.35	-0.15	0.52	-0.55	-0.38
12												-0.96	-0.06	0.47	0.37	-0.51	0.61
13													0.13	0.44	-0.44	0.50	0.44
14														-0.53	-0.72	0.61	0.58
15															-0.41	0.31	0.44
16																-0.69	0.57
17																	0.62
**12.05	9.47	6.42	12.27	12.56	12.36	12.11	12.60	12.59	11.82	9.31	8.72	8.71	9.09	6.46	10.10	11.93	10.17
***0.67	0.53	0.36	0.68	0.70	0.69	0.67	0.70	0.70	0.66	0.52	0.48	0.48	0.51	0.36	0.56	0.66	0.57

r = |0|–|0.4| No or weak correlation; r = |0.4|–|0.7| Moderate correlation; r = |0.7|–|1.0| Strong correlation. 1=Precipitation (mm); 2=Average daily temperature (°C); 3=Air humidity (%); 4=HTC; 5=I_{DM}; 6=K_h; 7=Leaf and stem biomass yield (t ha^{-1}); 8=Root biomass yield (t ha^{-1}); 9=Total plant biomass (t ha^{-1}); 10=Dry matter content of aboveground biomass (%); 11=Dry matter content of root residue biomass (%); 12=Root system productivity coefficient (in dry matter); 13=Share of root residues in total dry biomass of plants (%); 14=Leafiness of plants (%); 15=Share of stem part in plant biomass (%); 16=Share of generative part in plant biomass (%); 17=Survival rate of plants, (%); 18=IVC; ** Graf G; *** Graf G′. Significance level of $p < 0.05$, the interval r = 0.15–0.19, for $p < 0.01$ r = 0.20–0.25, for $p < 0.001$ r > 0.25.

In particular, the ability to intensive growth processes at lower temperatures during the growing season has already been noted. This is especially true for the early spring sowing of oilseed radish and the summer use of its biomass.

This level of temperature for white mustard and spring rape will already contribute to a decrease in the rate of growth processes and the size of the formed generative part of plants (Ahmad et al., 2012). At the same time, given the higher levels of dependence for relational quantities (ratios, coefficients) in comparison with the basic climatic parameters based on the generalizations of Agarwal et al. (2015), a more complex hierarchy of dependencies between the bioproductivity of oilseed radish plants and the climatic parameters of its growing season should be expected. With this in mind, we additionally applied multiple regression analysis to the data set (Table 3.5). According to the results of this regression assessment, a complex power law (second order) nature of the formation of bioproductivity of oilseed radish plants for both basic and derived parameters of the hydrothermal regime during the growing season was established by R^2_{adj} in the range of 0.800–0.951, which corresponds to a high tightness of the complex regression relationship according to the Chaddock scale. Based on the studies of Rameeh (2014), Han et al. (2020), Rajković et al. (2022) and by modeling the dynamic series of components x and y, their values were determined to obtain adequate maximum levels of the resulting indicators of plant bioproductivity that correspond to the long-term achievable level of climatic resources of the study area. This made it possible to determine the long-term optimum of the hydrothermal regime of oil radish vegetation in an array of two sowing dates. For the formation of above-ground biomass, the amount of precipitation for the period from sowing to flowering (BBCH 64–67) should be 240–255 mm at an average daily temperature of 18–20 °C with the formation of I_{DM} and K_h indicators at the level of 21–22 and 1.00–1.14, respectively.

For the formation of root biomass, on average, these indicators are 7.2% lower in terms of precipitation, 15.8% higher in terms of average daily temperature, and 15.8% and 14.7% lower in terms of$_{IDM}$ and$_{Kh}$, respectively. This difference is explained by the peculiarity of the root system formation in the soil substrate with the corresponding hydrothermal regime and physiological features of the delayed growth response of root systems to

Table 3.5

Regression models of dependence of oilseed radish bioproductivity on basic parameters of hydrothermal vegetation regime (in the total data set (sowing dates–repetitions–years of growth) for 2014–2023 (*N* = *160*)) (based on the results of the author's own research)

Resulting indicator	Components of the equation: x	Components of the equation: y	Regression equation of dependence	Multiple regression coefficient R/R^2_{adj}	Statistical significance criteria R
Leaf and stem biomass yield, t ha^{-1} (LSBY)	Precipitation, mm	Average daily temperature, °C	LSBY=13,4158-0.0037x+0.2923y+9.7657E-5x²+0,0048xy-0.0334y² **** *For the* $LSBY_{ma}$: *x=240.1; y=18.7°C*	0.951^{***} /0.893	F/SS_{total} = 80.789 (p = 0.000000), t_{05} = 7.35 (p = 0.00182)
Root biomass yield, t ha^{-1} (RBY)			RBY=14.8153-0,0076x-1.2633y+9.7858E-5x²+0.0014xy+0.0294y² *For the* RBY_{max}: *x=228.5; y=20.9°C*	0.972^{***} /0.930	F/SS_{total} = 116.460 (p = 0.00000), t_{05} = 13.20 (p = 0.000000)
Leaf and stem biomass yield, t ha^{-1} in dry matter ($LSBY_{DM}$)			$LSBY_{DM}$= 0.7987+0.0041x+0.1289y-5.9224E-6x²+0.0006xy-0.0057y² *For the* $LSBY_{DM\,max}$: *x=216.3; y=18.2°C*	0.938^{***} /0.846	F/SS_{total} = 25.719 (p = .0000595), t_{05} = 6.72 (p = 0.00682)
Root biomass yield, t ha^{-1} in dry matter (RBY_{DM})			RBY_{DM} = 4.7469-0.0107x-0.3982y+2.9518E-5x²+0.0007xy+0.0089y² *For the* $RBY_{DM\,max}$: *x=208.9; y=21.8°C*	0.950^{***} /0.891	F/SS_{total} = 36.690 (p = .0000195), t_{05} = 9.43 (p = 0.00217)
Leaf and stem biomass yield, t ha^{-1} (LSBY)	Aridity Index (I_{DM})	Humidity coefficient (K_h)	LSBY=7.6847+9.9413x-57.782y-1.0575x²+11.7904xy-31.9372y² *For the* $LSBY_{ma}$: *x=22.9; y=1.14*	0.981^{***} /0.951	F/SS_{total} = 88.485 (p = 0.000000), t_{05} = 7.942 (p = 0.0000)
Root biomass yield, t ha^{-1} (RBY)			RBY=2,5733+0,6683x-2.6161y+0.6215x²-7.9348xy+25.5887y² *For the* RBY_{max}: *x=20.7; y=1.32*	0.967^{***} /0.925	F/SS_{total} = 57.730 (p = 0.00004), t_{05} = 5/488 (p = 0.00193)
Leaf and stem biomass yield, t ha^{-1} in dry matter ($LSBY_{DM}$)			$LSBY_{DM}$=1.0683+0.676x-3.3215y-0.0293x²+0.2705xy-0.6023y² *For the* $LSBY_{DM\,max}$: *x=21.1; y=1.02*	0.906^{***} /0.800	F/SS_{total} = 39.000 (p = 0.00000), t_{05} = 7.611 (p = 0.0000)
Root biomass yield, t ha^{-1} in dry matter (RBY_{DM})			RBY_{DM} = 0.2148+0.3391x-1.5257y-0.0411x²+0.5154xy-1.6147y² *For the* $RBY_{DM\,max}$: *x=19.5; y=1.17*	0.949^{***} /0.888	F/SS_{total} = 76.451 (p = 0.00000), t_{05} = 9.177 (p = 0.00098)

*, **, *** Significant at 5%, 1%, 0.1% level probability, respectively; **** components of the equations at the maximum achievable level of plant bioproductivity.

the increase in weather stress noted in the studies of Williams et al. (2013) and Kul et al. (2021), as well as the peculiarities of the morphometry and anatomy of the root system of oilseed radish noted in our previous studies (Tsytsiura, 2020).

The results of a long-term comprehensive evaluation of oilseed radish by the criterion of plant bioproductivity and related derivative indicators that determine the possibility of adequate accumulation of both aboveground and underground mass allowed us to classify this crop as strategically valuable for use in the multi-service cover crop (MSCC) system. The determined statistically reliable system of correlation and regression dependencies of both basic indicators of biomass accumulation and important indicators of growth rates, leafiness, plant survival while maintaining the appropriate vitality tactics according to the criterion of vitality index for radically different sowing dates proved the effectiveness of using oil radish in the system of such MSCC components as 'cover crop', 'catch crop', 'green manure' and potentially 'biogas resource'.

The above statements are based on certain levels of bioproductivity, which, even in extremely stressful years in terms of moisture and hydrothermal conditions, ensure the formation of at least 2.5 t ha^{-1} of dry matter and in optimal years exceed the mark of 7.0 t ha^{-1}. Limiting its use in the MSCC system is moisture, which productively in the form of precipitation should reach the level of 150–200 mm with an optimum of 205–250 mm during the period from sowing to flowering (BBCH 64–67). The level of average daily temperature had a wide range from 14 to 22 °C. Based on this, the most appropriate option for using oil radish in the system of intermediate and green manure use is the option of early spring sowing, as well as the option of summer intermediate use with a shift in sowing time to late July-early August for areas of unstable and moderate moisture.

The correlation analysis confirmed the above conclusions about the role of hydrothermal conditions in the possible level of achievement of the total bioproductivity of oilseed radish plants (Table 3.6). According to the value of the correlation graph of the first type (Graf G), the formation of both aboveground and underground (root) biomass of oilseed radish plants had the highest total dependence of modular numerical values of correlation coefficients from the position of plant weight characteristics (interval 7.30–7.61). Among the hydrothermal factors of the growing season, this indicator was maximum for hydrometeorological coefficients such as HTC, I_{DM}, K_h (average >7.70). Among the parametric factors, the amount of precipitation played a more significant role in the system of formation of the total bioproductivity of plants than the level of average daily temperature (correlation coefficient 1.52) and relative humidity (correlation coefficient 2.18). According to the values of the correlation graph of the second type (Graf G′), the coefficient of determination was 51.84% for the Aridity Index (I_{DM}), 50.41% for the hydrothermal coefficient (HTC) and the humidification coefficient (K_h), 47.6% for the amount of precipitation, 20.3% for the average daily temperature and 9.6% for the relative humidity. On this basis, the determining factor in the formation of the total bioproductivity of oilseed radish plants was the total moisture supply during their vegetation period due to atmospheric moisture and the processes of change of this indicator in relation to evaporation, temperature dynamics and the rate of their growth and change over time. The determined lower dependence on the average daily temperature gives grounds to assert its adaptive resistance to low temperatures and the possibility of initiating growth processes in the early and ultra-early periods according to the sowing dates. At the same time, the direction of the dependence showed that the level of total biomass of oilseed radish plants with a high level of predicted probability will increase with increasing precipitation (dyx=92.2%) and high values of hydrothermal coefficients and ratios (dyx=81.0–88.4%). If we compare the obtained dependencies with the model parameters that were included in the predictive models of biomass formation for such species as spring and winter rape, white mustard in variants of their multiple use (Dorsainvil et al., 2005; Jing et al., 2016; Asgari et al., 2021), it should be noted that oilseed radish has certain advantages in terms of climate adaptation indicators.

In particular, the ability to intensive growth processes at lower temperatures during the growing season has already been noted. This is especially true for early spring sowing of oilseed radish. Thus, on average, over the 10-year period of research, the average daily air temperature was 14.5 °C for the period April-June (Table 3.1). Such a level of temperature for white mustard and spring rape will already contribute to a decrease in the rate of growth processes and the size of the formed generative part of plants (Ahmad et al., 2017). At the same time, taking into account the higher levels of dependence for relational quantities (ratios, coefficients) in comparison with the basic climatic parameters, based on the generalizations of Akbarzadeh A & Katsikas (2021), a more complex hierarchy of dependencies between the bioproductivity of oilseed radish plants and the climatic parameters of its growing season should be expected. That is, oilseed radish has a rather flexible adaptive mechanism that distinguishes it from other cruciferous plants in terms of the possibility of using it in the MSCC system. From the point of view of assessing the value of the respective crop for its use in green manure, reclamation (rehabilitation of degraded soils) and biogas potential, it is important to assess the biochemical composition of the formed biomass. The results of such an assessment for aboveground biomass for the studied sowing dates as of the date of the phenological optimal period of use are presented in Tables 3.7 and 3.8. To estimate and determine the average biochemical portfolio of oilseed radish, gradations of estimates of a number of cruciferous crops were applied in the studies of Ayres & Clements (2002), Azam et al. (2013), Villalobos & Brummer (2013), Winkler (2017), Bell et al. (2020), Keim et al. (2020), Castillo-Umaña et al. (2020), Bakker et al. (2021), Omokanye et al. (2023), Sánchez et al. (2023). Based on these studies, the formed aboveground biomass of oilseed radish plants should be attributed to high-protein with a range of crude protein content at the level of 12–23%$_{DM}$ with an increase in the indicator when changing the sowing dates from spring to summer with a ratio of 1.23. The high fat content of more than 3.0 %$_{DM}$ also actualizes the leaf and stem mass of oilseed radish from the point of view of its fodder value and high ash content of more than 12%$_{DM}$ against the background of high phosphorus, potassium, calcium and sulfur (based on the approaches of evaluation by Abe (1984), Justes & Richard, 2017), the effective possibility of using leaf mass simultaneously for fodder and green manure purposes has been proved in view of the recycling of nutrients through the system of their return to the soil through the use of plant residues and green fertilizers in the form of oilseed radish biomass. The relatively high cellulose content at the flowering stage of more than 18%$_{DM}$ in spring and more than 23%$_{DM}$ in summer sowing against the background of the previously noted features of accelerated plant development (‘biological aging’) in summer sowing and high overall rates of phenostage formation of plants indicates a steady trend of reducing the quality biochemical parameters of plant mass when used in later phases of the growing season. This is confirmed by comparing the content of not only cellulose but also the constituent derivatives NDF, ADF and ADL and is consistent with the findings of Azam et al. (2013), Herrmann et al. (2016) and Bell et al. (2020) on other cruciferous plant species. This is also indicated by a 1.5-fold increase in lignin content in plant mass (in the form of ADL) when comparing summer and spring sowing dates. Such a stable trend allowed us to determine the peculiarities of oilseed radish biomass formation at different sowing dates under study. Thus, for the spring sowing date, against the background of lower average daily temperatures and slow growth rates, the process of protein complex formation takes place under lower stressful temperature conditions, which, according to the studies of Sharma & Dubey (2019) and Zhou et al. (2023), contributes to the formation of plant tissues with a higher level of organic matter, higher water content with lower fiber and cellulose content, lower protein content and lower ash content.

Table 3.6

Pearson's correlation coefficients of dependence of oilseed radish bioproductivity parameters on hydrothermal parameters of the growing season (for a joint system of matching sowing dates–repetitions–years (*N=160*)) (based on the results of the author's own research)

1	2	3	4	5	6	7	8	9	10	11
1	-0.40	0.49	0.91	0.96	0.91	0.95	0.95	0.96	-0.51	0.52
2		-0.02	-0.71	-0.62	-0.71	-0.44	-0.53	-0.48	0.51	-0.54
3			0.29	0.37	0.29	0.52	0.36	0.49	-0.35	0.28
4				0.99	1.00	0.87	0.93	0.90	-0.57	0.61
5					0.99	0.91	0.96	0.94	-0.56	0.60
6						0.87	0.93	0.90	-0.57	0.61
7							0.94	0.99	-0.41	0.40
8								0.97	-0.63	0.66
9									-0.49	0.49
10										-0.96
**7.56	4.96	3.46	7.78	7.90	7.78	7.30	7.86	7.61	5.56	5.67
***0.69	0.45	0.31	0.71	0.72	0.71	0.66	0.71	0.69	0.51	0.52

r = |0|–|0.4| No or weak correlation; r = |0.4|–|0.7| Moderate correlation; r = |0.7|–|1.0| Strong correlation. 1=Precipitation (mm); 2=Average daily temperature (°C); 3=Air humidity (%); 4=HTC; 5=I_{DM}; 6=K_h; 7=Leaf and stem biomass yield (t ha^{-1}); 8=Root biomass yield (t ha^{-1}); 9=Total plant biomass (t ha^{-1}); 10=Root system productivity coefficient (in dry matter); 11=Share of root residues in total dry biomass of plants (%); ** Graf G; *** Graf G´. Significance level of $p < 0.05$, the interval r = 0.15–0.19, for $p < 0.01$ r = 0.20–0.25, for $p < 0.001$ r > 0.25.

Table 3.7

Chemical composition of oilseed radish leaf and stem mass in spring sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Year	Organic dry matter (ODM) ($\%_{DM}$)*		Crude protein (CP) ($\%_{DM}$)		Crude fat (CF) ($\%_{DM}$)		Crude fibre (CFb) ($\%_{DM}$)		Crude ash (CA) ($\%_{DM}$)		NDF ($\%_{DM}$)		ADF ($\%_{DM}$)		ADL ($\%_{DM}$)	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	87.29	2.50	17.55	2.78	3.02	0.24	19.22	0.64	12.71	0.59	36.91	0.52	24.12	0.42	5.85	0.12
2015	85.41	1.82	15.08	1.91	5.55	0.40	23.07	0.65	14.59	0.45	40.12	0.29	31.24	0.59	4.77	0.14
2016	86.72	1.74	14.29	1.29	3.89	0.16	21.75	0.42	13.28	0.57	36.88	0.42	25.09	0.51	3.89	0.21
2017	84.89	2.47	15.91	1.85	5.09	0.49	23.24	0.30	15.11	0.19	38.09	0.35	28.57	0.57	4.05	0.12
2018	85.95	1.88	15.12	0.56	4.53	0.10	21.52	1.00	14.05	0.27	36.17	0.28	26.62	0.39	3.35	0.09
2019	87.48	1.59	19.17	0.84	3.01	0.31	19.17	0.87	12.52	0.76	34.02	0.19	22.19	0.25	3.58	0.11
2020	87.12	2.13	14.19	1.25	3.28	0.12	20.97	0.83	12.88	0.24	35.39	0.44	24.97	0.39	3.37	0.15
2021	87.39	1.72	12.75	0.83	3.59	0.45	21.83	0.43	12.61	0.34	36.41	0.25	25.17	0.47	4.02	0.07
2022	87.73	0.81	14.56	1.27	3.87	0.66	22.19	0.58	12.27	0.81	37.58	0.57	25.91	0.21	3.81	0.18
2023	86.32	1.49	17.02	1.01	3.94	0.20	22.29	0.87	13.68	0.54	35.89	0.39	24.11	0.33	3.96	0.13
$\bar{x}$	86.63	0.96	15.56	1.89	3.98	0.85	21.53	1.40	13.37	0.96	36.75	1.65	25.80	2.54	4.07	0.75
***R_{min}	1.17-1.33	–	0.55-1.08	–	0.47-0.58	–	0.81-1.09	–	0.63-0.82	–	0.81-0.97	–	0.88-1.05	–	0.13-0.21	–
LSD_{05}	1.29	–	0.87	–	0.52	–	1.00	–	0.75	–	0.90	–	0.93	–	0.16	–

(End of Table 3.7)

Year	Cellulose ($\%_{DM}$)	Hemicellulose ($\%_{DM}$)	TKN (%DM)		TOC ($\%_{DM}$)		Phosphorus ($\%_{DM}$)		Potassium ($\%_{DM}$)		Calcium ($\%_{DM}$)		Sulfur ($\%_{DM}$)		GSL µmol g^{-1} DM	
	$\bar{x}$	$\bar{x}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	18.27	12.79	2.81	0.44	38.25	0.57	0.54	0.06	2.71	0.11	1.07	0.14	0.32	0.06	12.08	0.45
2015	26.47	8.88	2.41	0.31	40.22	0.81	0.62	0.05	3.96	0.19	0.97	0.12	0.42	0.09	13.52	0.43
2016	21.20	11.79	2.29	0.21	39.14	0.48	0.77	0.17	4.74	0.24	1.00	0.10	0.50	0.10	14.51	0.37
2017	24.52	9.52	2.55	0.30	41.12	0.65	0.85	0.08	5.72	0.38	1.15	0.15	0.59	0.11	16.08	0.87
2018	23.27	9.55	2.42	0.09	39.77	0.78	0.69	0.07	3.74	0.20	1.03	0.08	0.52	0.06	15.56	0.57
2019	18.61	11.83	3.07	0.13	37.14	1.14	0.52	0.05	2.25	0.11	0.81	0.18	0.35	0.12	11.89	0.44
2020	21.60	10.42	2.27	0.20	40.09	0.43	0.63	0.08	4.08	0.16	0.92	0.07	0.35	0.05	12.44	0.60
2021	21.15	11.24	2.04	0.13	37.95	0.73	0.48	0.09	2.87	0.37	0.93	0.17	0.39	0.05	12.77	0.40
2022	22.10	11.67	2.33	0.20	38.44	0.46	0.51	0.03	3.03	0.10	0.89	0.10	0.41	0.08	13.84	0.52
2023	20.15	11.78	2.72	0.16	38.89	0.42	0.61	0.06	3.19	0.31	0.82	0.07	0.34	0.09	12.97	0.59
$\bar{X}$	21.73	10.95	2.49	0.30	39.10	1.21	0.62	0.12	3.63	1.04	0.96	0.11	0.42	0.09	13.57	1.44
R_{min}	–	–	0.20-0.39	–	0.89-1.05	–	0.09-0.14	–	0.25-0.39	–	0.15-0.20	–	0.10-0.14	–	0.19-0.36	–
LSD_{05}	–	–	0.34	–	0.98	–	0.12	–	0.34	–	0.18	–	0.12	–	0.23	–

*The indicator of transformation between %DM and g kg^{-1}_{DM} = %DM x 10.**SD – standard deviation; ***Tukey's test (R_{min} for $p_{adj} < 0.05$).

For the summer sowing period, when plants are formed at significantly higher levels of average daily temperature and more stressful conditions of hydrothermal vegetation regime (Table 3.1), biochemical processes of the reverse nature occur. A similar system of correlations was noted for white mustard at different periods of its use (Ţiţei (2022)) and some representatives of the radish genus (Ayres & Clements, 2002). This is also confirmed by the results of comparing the main biochemical components of the spring sowing period with similar long-term averages of the summer one. The obtained coefficients of this ratio in the interval of research years for ODM 1.03-1.11, CP 0.77-0.85, CF 0.74-0.88, CFb 0.79–0.89, ADL 0.59–0.71, Cellulose 0.81–0.89, Hemicellulose 0.73–0.85, TNC 0.74–0.85, TOC 0.91–0.99, P 0.89–0.98, K 0.85–0.94, Ca 0.87–0.95, S 0.79–0.90, GSL 0.82–0.88. As a result, taking into account a number of studies (Clark 2008; Hansen et al., 2021, 2022; Jauhiainen 2022; Launay et al., 2022; Fajobi et al., 2023; Lallement et al., 2023; Lymperatou et al., 2023; Manyi-Lohn & Lues, 2023), the leaf mass of oilseed radish of different sowing dates will have different criterion evaluation in the MSCC system.

At the same time, due to the increasing stress of general environmental factors (Latief et al. (2017)), the overall variability of the obtained average values in terms of years of research is also increasing. According to the results of the presented estimates, the coefficient of variation (CV) of the average for the general data set for the summer sowing period of oilseed radish had an average growth coefficient of 1.21 compared to the indicators of the spring sowing period. Such features lead to an increase in the variable component in assessing the effectiveness of the use of the obtained oilseed radish biomass for the criterion goals of the MSCC system.

It should also be noted that based on studies that have studied oilseed radish in the management system of cover crops for different purposes (Herrmann et al., 2016; Blume et al., 2020; Gamba et al., 2021; Hansen et al. 2021; Lövgren, 2022; Olofsson & Ernfors, 2022; Kemper et al., 2023), the results of biochemical evaluation presented in Tables 3–4 have certain differences. Thus, the crude protein content at the spring sowing date was 0.9–1.5% $_{DM}$ lower than the value, and at the summer sowing date it did not reach the value of 25–27%$_{DM}$ noted in the above studies. The content of lignin, cellulose and its derivatives is 3.8–7.7%$_{DM}$ higher than in the estimates of Herrmann et al. (2016) and Hansen et al. (2021). The total organic carbon (TOC) content according to our estimates had a relatively stable value with fluctuations in the range of 38–42%$_{DM}$, although in the study by Hansen et al. (2021) this value had a narrower interval of 39–40%$_{DM}$, and in the study by Gamba et al. (2021) for the radish genus, the possibility of its value at the level of 35–44%$_{DM}$ was noted. The detail of the content of the main elements (nitrogen, phosphorus and potassium) was estimated for two seasons with different weather conditions in the study by Hansen et al. 2021. In comparison with the data of this study, for oilseed radish on gray forest soils under conditions of unstable moisture, the phosphorus content was found to be 0.13–0.33%$_{DM}$ higher, the potassium content was 0.72–1.12%$_{DM}$ lower, and the calcium content was 0.15–0.24%$_{DM}$ higher.

The nitrogen content was lower by 0.18–0.35%DM. Regarding the comparison of the biochemical profile of oilseed radish with other cruciferous crops such as white mustard, spring and winter rape, and radish (according to Swarcewicz et al. (2013), Li et al. (2019), Abdallah et al. (2020), Liu et al. (2020), Tian & Deng (2020), Wang et al. (2022), Jacob et al. (2022), Rajković et al. (2022), Ţiţei (2022), Oliveira & Słomka (2021), Shitophyta et al. (2023), Israt & Parimal (2023)) was determined to be 3.4–8% lower. 7 %DM crude protein content, at or above 1.3–2.4%DM crude fat content, at or below 1.7–2.2%DM ash content, at or below 0.7–2.5%DM lignin content, below 1.9–6.1%DM crude fiber content, higher potassium content by 1.8–3.7%DM, equal or lower by 0.12–0.22%DM phosphorus content, equal calcium content and equal or lower by 0.27–0.35%DM sulfur content.

The presented comparison confirms the value of oilseed radish leaf mass as a potential candidate for use in green manure system and possible use for anaerobic fermentation for biogas production. For conditions of unstable moisture on soils with medium fertility potential, which include Grey forest soils (Greyi-Luvic Phaeozems (IUSS, 2015)).

Table 3.8

Chemical composition of oilseed radish leaf and stem mass in summer sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Year	Organic dry matter (ODM) ($\%_{DM}$)*		Crude protein (CP) ($\%_{DM}$)		Crude fat (CF) ($\%_{DM}$)		Crude fibre (CFb) ($\%_{DM}$)		Crude ash (CA) ($\%_{DM}$)		NDF ($\%_{DM}$)		ADF ($\%_{DM}$)		ADL ($\%_{DM}$)	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	85.08	0.99	17.44	1.31	4.17	0.82	23.32	0.82	14.92	0.90	42.31	0.52	29.89	0.42	6.12	0.12
2015	83.79	0.87	14.88	1.61	5.82	0.62	26.72	0.70	16.21	0.72	46.12	0.29	33.17	0.59	6.61	0.14
2016	84.08	1.78	18.38	2.15	4.40	0.40	23.89	0.61	15.92	0.33	42.87	0.42	30.05	0.51	6.18	0.21
2017	85.36	3.32	19.88	2.00	4.29	0.33	22.97	0.75	14.64	0.60	41.92	0.35	29.19	0.57	5.74	0.12
2018	84.80	1.71	20.75	2.42	4.78	1.09	23.69	0.99	15.20	0.63	42.30	0.28	29.68	0.39	5.92	0.09
2019	83.21	1.13	16.13	1.65	5.02	0.48	25.33	1.03	16.79	0.35	44.35	0.19	31.87	0.25	6.48	0.11
2020	84.63	0.74	20.44	1.39	4.55	0.79	24.17	0.85	15.37	1.11	44.11	0.44	31.05	0.39	6.25	0.15
2021	83.56	1.93	19.31	1.52	4.72	0.28	24.85	0.64	16.44	0.86	44.55	0.25	31.27	0.47	6.29	0.07
2022	85.03	0.67	22.94	3.26	4.08	0.65	22.51	0.79	14.97	0.44	42.37	0.57	28.97	0.21	5.52	0.18
2023	84.42	0.54	21.44	3.13	4.27	0.32	23.92	0.64	15.58	0.92	43.09	0.39	30.34	0.33	6.09	0.13
$\bar{x}$	84.40	0.71	19.16	2.48	4.61	0.52	24.14	1.23	15.60	0.71	43.40	1.34	30.55	1.30	6.12	0.33
***R_{min}	0.81-0.96	–	1.05-1.28	–	0.82-0.96	–	0.92-1.19	–	0.88-1,12	–	0.99-1.36	–	1.53-1.81	–	0.32-0.48	–
LSD_{05}	0.92	–	1.14	–	0.91	–	1.14	–	1.05	–	1.24	–	1.64	–	0.37	–

(End of Table 3.8)

Year	Cellulose ($\%_{DM}$)	Hemicellulose ($\%_{DM}$)	TKN (%DM)		TOC ($\%_{DM}$)		Phosphorus ($\%_{DM}$)		Potassium ($\%_{DM}$)		Calcium ($\%_{DM}$)		Sulfur ($\%_{DM}$)		GSL µmol g^{-1} DM	
	$\bar{x}$	$\bar{x}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	23.77	12.42	2.79	0.21	41.03	1.34	0.57	0.09	3.52	0.36	1.07	0.17	0.41	0.11	18.55	1.04
2015	26.56	12.95	2.38	0.26	39.82	1.31	0.71	0.10	4.71	0.20	1.13	0.26	0.68	0.06	21.58	1.56
2016	23.87	12.82	2.94	0.34	40.59	1.78	0.67	0.07	3.89	0.14	1.09	0.29	0.39	0.04	18.19	1.09
2017	23.45	12.73	3.18	0.32	38.51	0.79	0.59	0.09	3.33	0.46	0.92	0.18	0.35	0.06	17.92	0.60
2018	23.76	12.62	3.32	0.39	38.09	1.71	0.65	0.07	4.35	0.16	0.85	0.09	0.53	0.04	21.02	0.53
2019	25.39	12.48	2.58	0.26	40.87	0.82	0.78	0.07	4.98	0.15	1.28	0.23	0.56	0.17	21.19	0.56
2020	24.80	13.06	3.27	0.22	38.44	0.85	0.54	0.06	3.39	0.23	1.09	0.15	0.47	0.05	19.75	0.52
2021	24.98	13.28	3.09	0.24	41.29	0.76	0.64	0.09	3.57	0.34	1.05	0.09	0.59	0.07	21.53	0.70
2022	23.45	13.40	3.67	0.52	38.98	1.73	0.52	0.03	3.05	0.20	0.67	0.18	0.31	0.09	17.17	0.63
2023	24.25	12.75	3.43	0.50	39.15	0.89	0.59	0.08	3.82	0.40	0.95	0.11	0.49	0.09	20.09	0.47
$\bar{x}$	24.43	12.85	3.07	0.40	39.68	1.20	0.63	0.08	3.86	0.63	1.01	0.17	0.48	0.12	19.70	1.64
***R_{min}	–	–	0.41-0.53	–	1.73-1.95	–	0.07-0.15	–	0.32-0.44	–	0.21-0.32	–	0.08-0.15	–	0.31-0..54	–
LSD_{05}	–	–	0.49	–	1.82	–	0.11	–	0.41	–	0.27	–	0.12	–	0.43	–

*The indicator of transformation between %DM and g $kg^{-1}{}_{DM}$ = %DM x 10. **SD – standard deviation; ***Tukey's test (R_{min} for $p_{adj} < 0.05$).

Regarding the content of glucosinolates, this indicator is important in the MSCC criterion system from the point of view of providing the appropriate crop with a broad spectrum biofumigation effect due to the incorporation of the formed plant biomass into the soil, which helps to reduce the germination of weed seeds, soil fungicidal effect against a number of harmful pathogens and reduction of soil pests, in particular, various species of nematodes and pests of the polyphagous group with a soil development cycle at the larval stage due to soil transformation of glucosinolates into isothiocyanates (ITC) (Śmiechowska et al., 2010; Edwards & Ploeg, 2014), which are commercially used to control numerous crop pests, including nematodes, pathogens, and weeds (Sang et al., 1984; Kirkegaard & Sarwar, 1998; Sarıkamıs et al., 2017; Blažević et al., 2020; Yan et al., 2023; Redha et al., 2023). Additionally, the presence of glucosinolates at certain concentration levels is desirable for intermediate cover crops, especially in summer sowing, to control a number of entomophages and diseases, which guarantees the necessary level of plant survival and guaranteeing the appropriate technological planting density and the desired bioproductivity (Zachariah, 2011; Bhandari et al, 2015; Perniola et al., 2019; Andini, 2020; Ait Kaci Ahmed et al., 2022; Abdel-Massih et al., 2023). It is especially relevant for the control of cruciferous fleas, the harmfulness of which in the agrocenosis of oilseed radish causes a significant decrease in plant survival already at the germination stage (up to 20–60% reduction). As a result, this significantly reduces the indicators of the formed aboveground biomass, worsens its quality and forms a reduced soil cover, especially during summer sowing, in conditions of a more favorable temperature regime for intensive feeding of this pest (Tsytsiura, 2024). In this regard, it was proved that the glucosinolate content had a high direct correlation with the level of harmfulness of various cruciferous pests, including cruciferous fleas (Bohinc et al., 2013). In view of these facts, the content of glucosinolates in aboveground biomass is of paramount importance in the criterion evaluation of crops in the MSCC system in such areas as 'cover crop', 'catch crop', 'green manure' for the formation of an agrocenosis of a sufficient level of bioproductivity while maintaining the appropriate biochemical quality indicators.

At the same time, the high concentration of these compounds significantly narrows the use of this species in the MSCC system as a ‘fodder crop’, reducing the feed value of the plant and can cause poor compatibility and a number of disorders in animals (Prieto et al, 2019) and also reduces the efficiency of such a direction as ‘biogas crop’ due to the formation of certain processes of inhibition of the intensity of anaerobic fermentation of the resulting leaf-stem mass (Cleemput, 2011; Al Seadi et al., 2013; Herrmann et al., 2016; Tsytsiura 2023b). The content of glucosinolates is also important for cruciferous crops used as ‘catch crops’, since it has been established that these compounds are involved in the formation of plant stress responses to abiotic factors, and their intensive growth has high levels of significant correlation with the increase in the overall stress of the growing season by climatic parameters, which is especially important for intermediate crops that are often grown in the summer-autumn period with increasingly stressful environmental conditions (Chowdhury, 2022; Lei et al. , 2022; Zhang et al., 2022).

Long-term assessment of the direct and derived glucosinolate potential of cruciferous plants (Sang et al., 1984; Kirkegaard & Sarwar, 1998; Bellostas et al., 2004; Ciska et al., 2008; Velasco et al., 2008; Edwards & Ploeg, 2014; Bhandari et al., 2015; Yi et al., 2016; Ricardo et al., 2018; Liu et al., 2020; Wu et al, 2021; Mocniak et al., 2023; Iwar et al., 2024) proved high interspecific variability of their content as well as high variability of concentration in the aboveground parts of the plant depending on the phenological phase of development and abiotic environmental conditions. Thus, the total content of glucosinolates and different cruciferous plant species ranged from 1.97 to 140.9 μmol g^{-1} DM with a maximum concentration in seeds and generative parts and a minimum in the early stages of vegetation in leaves and roots. At the same time, it was noted (Velasco et al., 2008) that the concentration of glucosinolates among the cruciferous groups was maximum for leafy cruciferous plants (up to 26 μmol g^{-1} DM), lower values were noted for the group of fodder cruciferous plants (up to 24 μmol g^{-1} DM) and classical oilseed cruciferous plants had the lowest level of the indicator (12-16 μmol g^{-1} DM). In the study by Bhandari et al. (2015), the lowest GSL concentrations were observed in representatives of the genus radish across all tissues examined (18-40 μmol g^{-1} DM).

The long-term average content of glucosinolates in the aboveground biomass of oilseed radish was 13.57 μmol g^{-1} DM (CV 8.32%) in spring and 19.70 μmol g^{-1} DM (CV 10.58%) in summer sowing, which confirms the increase in their concentration with an increase in the overall stress of the growing season, taking into account the level of average daily temperatures (Table 1). Regarding the assessment of the level of the obtained values, in various studies on oilseed radish at the flowering stage, the level of glucosinolates was in the range of 9–41 μmol g^{-1} DM and was 1.2–1.5 times higher in inflorescences compared to leaves and stem (Gimsing & Kirkegaard, 2006; Bohinc et al., 2013; Duff et al., 2020). At the same time, as for other cruciferous crops recommended for use in the MSCC system, for white mustard the average glucosinolate content (on average per plant) for the flowering phase was in the range of 11-56 μmol g-1 DM (Sang et al, 1984; Kirkegaard & Sarwar, 1999; Bohinc et al., 2013; Ciska et al., 2008; Tian & Deng, 2020), spring rape 9-44 μmol g-1 DM (Sang et al., 1984; Birch et al, 1992), winter rape 8-51 μmol g^{-1} DM (Sang et al., 1984; Milford & Evans, 1991; Kirkegaard & Sarwar, 1999; Ciska et al., 2008; Yasumoto et al., 2010; Bohinc et al., 2013; Salisbury et al., 2018). Thus, long-term data on the content of glucosinolates in oilseed radish (Table 3–4) give grounds to attribute it to cruciferous crops with high biofumigation potential for both spring and summer use.

It is noted (Couëdel et al., 2018a, 2019) that the biochemical assessment of the leaf mass of plants used as cover crops for multipurpose use requires a system of appropriate ratios that determine the processes of decomposition, mineralization, accumulation and the predicted intensity of anaerobic fermentation. These ratios are widely used by the scientific community and proposed in the analysis of Hansen et al. (2021, 2022), Thiébeau et al. (2021), Quintarelli et al. (2022), Allam et al. (2023), Yousefi et al. (2024). The results of this assessment are presented in Table 3.9. According to a number of studies (Kriaučiūnienė et al., 2012; Jahanzad et al., 2016; Sousa et al., 2019; Liu et al., 2020; Toleikiene et al., 2020; Dorissant et al., 2022; Silva et al., 2023), the C/N ratio is decisive in the decomposition rate of green biomass that is incorporated into the soil.

From the point of view of these criteria, the biomass of oilseed radish at the interval value of C/N ratio, taking into account the SD value in the context of research years 8.73-20.11 with interannual variation of 12.3% for spring sowing and 15.4% for summer sowing (Table 5) fully meets the criteria of ‘fodder crop’ and ‘green manure’ and is predicted to ensure rapid decomposition of fresh biomass in the soil, especially under conditions of sufficient moisture supply against the background of high average daily temperatures. These values also indicate a significant proportion of leaves and inflorescences in the total biomass of oilseed radish, especially at the summer sowing date, which is consistent with the findings of Kriaučiūnienė et al. (2012) on the decomposition rates of different parts of cruciferous plant species.

It should also be noted that in the case of summer sowing of oilseed radish , according to a number of studies (Wadman & de Haan, 1997; Hadas et al., 2004; Flores-Sánchez et al., 2016; Drost et al., 2019; Salume et al, 2020) decomposition rates, despite the 17% lower average C/N ratio over the entire evaluation period, will have predictably slower decomposition rates due to the significantly lower temperature level during the period of direct use of biomass in the form of green manure (Table 1). Taking into account that the optimal value is a certain balance C/N value, which provides a positive ratio between the rate of decomposition and subsequent humus accumulation and immobilization of mineral nutrients, which is in the range from 13 to 25 depending on weather conditions, soil type and the nature of the use of the corresponding cover crop (according to Wadman & de Haan, 1997) and positively correlates with this ratio in classical cattle manure 16.6-25.0 (according to Pan et al, 2021) – the biomass formed during spring sowing had a higher degree of compliance with these intervals for green manure use. However, according to the recommendations of Couëdel et al. (2019) and Hansen et al. (2021), its use can be optimized by using oilseed radish in mixed crops with cereals and legumes, as well as using additional plant materials for combined green manure (e.g. straw).

The determined long-term average C/N ratio allowed us to classify oilseed radish as a candidate for the 'fodder crop' in the MSCC system, since in this case the value of the indicator is considered from the standpoint of increased protein content, i.e. higher total nitrogen content with optimization of fiber and non-nitrogenous compounds (lower carbon content). As a result, the optimal value of the C/N ratio is in the range of 8–15 (Li & Zhou, 2002). It has been noted (Guarino et al., 2016; Herrmann et al., 2016; Dębowski et al., 2022; Manyi-Loh. & Lues, 2023; Tsytsiura, 2023a) that the optimal C/N value for anaerobic biomass dehydration in biogas production technologies is in the range of 20-30 with an interval of possible technological deviations in the range of 10 to 30. At low values of the C/N ratio, the concentration of the ammonium form of nitrogen increases significantly and the microbial process of anaerobic fermentation is inhibited (Cerón-Vivas et al., 2019; Choi et al., 2020).

Table 3.9

The main indicators of quality of oilseed radish aboveground biomass for different terms of sowing, 2014–2023 (based on the results of the author's own research)

Year	C/N ratio				C/P ratio				C/S ratio				Carbohydrates (CH) ($\%_{DM}$)			
	*SprS		SumS		SprS		SumS		SprS		SumS		SprS		SumS	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	13.94	2.80	14.77	1.18	71.41	7.27	73.59	13.45	122.24	19.90	106.69	34.14	66.71	3.37	64.43	1.33
2015	16.86	1.81	16.86	1.60	65.12	4.58	57.06	9.16	98.68	18.50	58.94	5.65	64.80	2.05	65.01	1.98
2016	17.20	1.67	13.99	2.18	53.27	14.66	61.25	8.23	80.55	15.57	105.36	15.79	68.52	1.90	62.44	1.95
2017	16.28	1.83	12.21	1.35	48.70	4.49	66.25	9.09	71.71	14.05	112.41	18.62	63.86	2.49	62.45	2.22
2018	16.45	0.71	11.58	1.41	58.20	7.29	59.08	6.73	77.13	7.97	72.27	7.92	66.30	0.83	60.60	1.90
2019	12.12	0.86	15.97	1.73	72.13	8.98	52.73	4.93	115.31	35.43	80.62	33.69	65.28	1.71	63.31	1.97
2020	17.75	1.37	11.81	1.03	64.30	7.13	71.70	6.70	116.73	19.14	82.29	6.68	69.65	1.37	61.08	1.45
2021	18.67	1.44	13.42	1.06	80.82	12.41	65.64	10.32	98.56	14.00	70.80	9.22	71.05	0.81	60.88	1.57
2022	16.59	1.48	10.84	2.11	75.56	4.00	75.03	2.14	96.60	18.90	134.31	40.91	69.30	1.00	59.18	2.97
2023	14.34	0.96	11.58	1.51	64.24	6.67	67.15	8.31	120.76	31.85	82.23	17.63	65.38	1.71	59.93	3.24
$\bar{x}$	16.02	2.36	13.30	2.40	65.37	12.13	64.95	10.23	99.83	25.78	90.59	29.80	67.08	2.83	61.93	2.63
LSD_{05}	2.30	–	2.05	–	5.79	–	3.89	–	12.81	–	10.55	–	2.71	–	3.08	–

(End of Table 3.9)

Year	Residue quality (RQ) ($\%_{DM}$)				Accumulation in aboveground biomass (kg ha^{-1})											
					Nitrogen***				Phosphorus				Potassium			
	SprS		SumS		SprS		SumS		SprS		SumS		SprS		SumS	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	81.36	0.82	81.46	0.88	114.6	15.27	93.94	11.22	22.14	2.70	19.50	5.27	111.15	9.64	118.21	12.98
2015	86.35	0.84	80.44	0.72	68.34	8.05	39.51	4.58	17.62	1.71	11.88	2.50	112.56	9.22	78.38	7.71
2016	84.32	0.98	81.00	1.33	69.32	8.38	98.71	14.96	23.19	4.95	22.32	0.16	143.27	10.32	130.87	15.65
2017	86.43	0.65	81.53	1.84	53.28	6.04	108.00	12.61	17.76	1.65	20.04	3.26	119.68	10.73	113.53	20.25
2018	87.10	1.15	81.46	0.78	51.08	9.02	114.45	14.26	14.58	3.01	22.42	2.64	78.54	10.69	150.09	11.32
2019	84.59	0.88	81.04	0.78	123.8	10.91	44.75	5.09	21.05	3.56	13.56	1.81	90.61	5.69	86.49	7.42
2020	86.21	1.08	80.69	0.68	89.21	8.25	59.46	6.82	24.79	3.46	9.77	0.74	160.26	4.34	61.51	5.40
2021	84.74	1.33	80.43	0.52	58.03	4.48	84.48	10.67	13.88	4.07	17.56	3.53	81.32	8.28	97.64	13.52
2022	84.52	1.07	81.08	0.71	65.62	7.09	122.58	21.80	14.35	1.12	17.28	1.17	85.26	4.59	101.62	10.79
2023	84.26	1.39	81.16	0.98	87.14	5.89	115.51	17.38	19.50	1.36	19.79	1.68	101.96	6.37	129.07	18.97
$\bar{x}$	84.99	1.83	81.03	0.95	78.04	25.40	88.14	31.25	18.88	4.57	17.41	4.80	108.46	25.52	106.74	22.25
LSD_{05}	1.50	–	2.17	–	8.69		9.73		4.33		3.86		8.77		10.72	

Year		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	$\bar{x}$	LSD_{05}
Ca accumulation (kg ha^{-1})	SprS	44.05	27.48	30.27	24.04	21.75	32.28	36.17	26.79	25.05	26.31	29.42	3.69
	SumS	36.27	18.69	36.90	31.04	29.24	22.09	19.72	28.81	22.10	32.03	27.69	4.27
S accumulation (kg ha^{-1})	SprS	13.18	11.89	15.15	12.31	11.00	14.29	13.78	11.10	11.52	10.82	12.50	2.34
	SumS	14.09	11.32	13.02	11.87	18.24	9.75	8.51	16.19	10.36	16.53	12.99	3.82
GSL productivity (mol ha^{-1})	SprS	49.5	38.4	43.8	33.6	32.7	47.9	48.9	36.4	38.9	41.5	41.2	0.17
	SumS	62.5	35.8	61.1	60.8	72.5	36.7	36.0	58.8	57.2	67.7	54.9	0.35
Equivalent cattle manure, t ha^{-1}	SprS	23.0	18.9	22.8	18.9	13.7	21.7	26.1	13.9	15.2	19.6	23.0	–
	SumS	22.0	12.6	24.3	23.1	28.1	14.2	12.5	19.2	23.1	25.6	22.0	–

*SprS – Spring sowing; SumS – Summer sowing. **SD – standard deviation; *** transformation from kg ha^{-1} to g m^{-2} by dividing the value by 10.

Based on this, the most appropriate option for oilseed radish would be the use of pre-prepared biomass both through silage and through co-fermentation of fresh mass with other plant or organic resources (according to the technological solutions proposed by Wang et al, 2012), as well as the use of cofermentation and inoculum to guarantee an optimal start of the process, according to a ssuch technological applications in the application to other cruciferous crops (Carvalho et al., 2011; Herrmann et al., 2016; Oliveira & Słomka, 2021) and the results of our previous studies. We proved (Tsytsiura, 2023c) that silage fermentation of oilseed radish leaf mass allows to increase the C/N ratio by 3-6 units depending on the phenological phase of plants during the formation of silage mass, and the use of inoculum starter helps to optimize the accumulation curve of the generated biomethane and intensifies the digestion process.

Regarding the obtained C/N ratio in our studies compared to the data for other cruciferous crops used in MSCC variants, it should be noted that for most cruciferous species this indicator in different years at the flowering stage was in the range of 12–23 for spring sowing and 10–18 for summer sowing (Herrmann et al, 2016; Li et al., 2019; Blume et al., 2020; Keim et al., 2020; Liu et al., 2020; Hansen et al., 2021; Ţiţei, 2022). Such results confirm the high potential of oilseed radish in the MSCC criterion system in comparison with the already widely used cruciferous crops.

It is also important to evaluate the C/P ratio, which, according to Ngatia et al. (2014), is a certain expression of the relationship between soil immobilization of mobile phosphorus forms and the efficiency of its replenishment by biomass introduced into the soil. This ratio affects the nature of the microbiological decomposition of green manure, especially in soils depleted in mobile phosphorus forms. According to Rinasoa et al. (2022), the optimal option for green manure application of the formed biomass is its high phosphorus content and low C/P ratio.

This ensures the maintenance of intensive rates of biomass decomposition in the soil with a positive balance of phosphorus release (Amy et al., 2024). According to this criterion, the leaf and stem mass of oilseed radish meets the required disparity between the phosphorus content and its ratio to organic carbon with a long-term average value not exceeding 70 with an interannual variation of 15.3% in spring and 11.34% in summer sowing. For example, in cereal green manure, this figure was 115–140, and in legumes

110–125 (Hansen et al., 2021). At the same time, the difference between the average long-term value for both sowing dates was not significant. Taking into account the above, oilseed radish will be effective for green manuring of soils poor in mobile phosphorus and in options for restoring a positive phosphorus balance in soils under organic fertilization systems. It should also be noted that in comparison with other cruciferous crops, oilseed radish is characterized by a high phosphorus content in terms of dry matter (average long-term level of 0.62–0.63 $\%_{DM}$ (Table 34)). In particular, for white mustard, this indicator ranges from 0.24–0.70 $\%_{DM}$ (Swarcewicz et al., 2013; Tian & Deng, 2020; Ţiţei, 2022; Israt & Parimal, 2023), for spring and winter rape in the range of 0.36–0.82 $\%_{DM}$ (Nobile et al., 2019; Amy et al., 2024).

Important for assessing the biofumigation potential of plants is the C/S ratio, which is a relative indicator of the presence of glucosinolates in plant biomass, since the biochemical composition of some chemical compounds belonging to this group of substances are sulfur-containing (De Kok et al., 2012; Pekarek et al., 2013; Galaup, 2018; Couëdel et al., 2019; Duff et al., 2020). It has been established that an effective green manure option with an overall biofumigation effect is possible at a C/S ratio of no more than 120 (Kirkegaard & Sarwar, 1998; Zachariah, 2011). According to our estimates, it was in the range from 71 to 122 for spring sowing and from 59 to 134 for summer sowing, which meets the requirements of an effective biofumigation process for green manure use of the formed biomass. During the summer sowing period, this indicator had a 1.36 times higher level of interannual variation than during the spring sowing period (25.6%) and significantly lower than its long-term average value by 9.24 units. This character of the formation of the indicator, in addition to the hydrothermal features of the growing season in the summer sowing period, is also explained by the lower proportion of the generative part and the larger proportion of leaves, which, given the data on the content of glucosinolates in different parts of cruciferous plants (Bohinc et al., 2013; Perniola et al., 2019), naturally reduces the content of sulfur-containing compounds in the formed biomass. This is confirmed by comparing the maximum C/S value of 134.31 for the conditions of summer sowing in 2022, for which the highest amount of precipitation of 436.6 mm at moderate temperature was recorded in the cycle of years of research of this period

(Table 3.1), which contributed to intensive growth vegetative processes in accordance with the previously described features of the formation of oilseed radish biomass and the lowest percentage of the generative part of plants. The biofumigation potential of oilseed radish was also confirmed by the value of glucosinolate productivity for both sowing dates (Table 5). The obtained values in the range of 32.7–49.5 mol ha^{-1} (with an interannual CV of 15.1%) for spring sowing and 36.0–72.5 mol ha^{-1} (24.9%) for summer sowing are in line with the study of Duff et al. (2020), who noted the effective level of this indicator for achieving multiple goals of soil biofumigation by green manure in the case of spring and summer sowing, depending on the type of cruciferous plants in the range of 30–105 mol ha^{-1}. At the same time, the interval of 60–105 mol ha^{-1} was achieved by using different types of mustard (White mustard (*Sinapis alba*), Ethiopian mustard (*Brassica carinata*), Indian mustard (*Brassica juncea*), Fodder mustard (*Brassica napus*), Black mustard (*Brassica nigra*)) in pure sowings or in various mixtures with radishes (such species-specific trademarks as 'Tillage Radish', 'Terranova Radish', 'Black Jack Radish'). Thus, at the achieved level of glucosinolate accumulation, the studied species of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) can be effectively used at both sowing dates in the soil rehabilitation system through the process of green manure biofumigation. At the same time, the issue of combining oilseed radish with other cruciferous species under conditions of unstable moisture should be further investigated in the future.

The criterion value of the leaf-stem aboveground mass of oilseed radish in the MSCC system is also confirmed by the level of carbohydrates, which determine the dynamics of mass decomposition and the nature of such decomposition in terms of released substances and their subsequent positive effect on the microbiological activity of the soil and the promotion of its self-aggregation. From this point of view, the value of this indicator in the range of 55-60 %DM fully meets the requirements for the effective green manure utilization of the biomass of this plant species (Liu et al., 2020; Israt & Parimal, 2023).

In addition, it has been proven that carbohydrates are energy-providing feed components composed of carbon, hydrogen, and oxygen. They should make up about $75\%_{DM}$ of an animal's diet (Navarro et al., 2019). Accordingly, according to this indicator, the biomass of oilseed radish with a carbonate content of up to 50–70 $\%_{DM}$ needs to be improved in terms of the desired compatible use, in particular with cereals and legumes, which is confirmed in a number of studies (Ayres & Clements, 2002; Mbambalala et al., 2023; Sánchez et al., 2023).

It is argued that biomass, particularly agricultural residues and biomass rich in structural carbohydrates, offers significant potential for sustainable biogas production (Venslauskas et al., 2024). At the same time, for most crops with high biogas production potential, the carbohydrate content should reach 65–75$\%_{DM}$ (Herrmann et al., 2016). Based on these statements, the leaf mass of oilseed radish formed by the plant during the spring sowing period with an average long-term carbonate content of 67.08$\%_{DM}$ was technologically more suitable for biogas production than the same during the summer sowing period, which is consistent with the results of our previous studies (Tsytsiura, 2023a).

To evaluate the possibility of effective use of oilseed radish leaf mass in the form of mulching with spreading of the chopped mass on the soil surface (Duff et al. 2020), the residue quality (RQ) index in the traditional variation (Quemada and Cabrera, 1995) was adapted. The obtained long-term average of 84.99$\%_{DM}$ for spring and 81.03$\%_{DM}$ for summer sowing, in line with similar estimates in Bajgai et al. (2014), Thiébeau et al. (2021) and Sharma et al. (2022), prove the potential use of oilseed radish biomass for green mulching (according to Nithisha et al. 2022) in the system of creating a protective mulching layer in the variants of bioconservation agriculture. This type of technological solution is predicted to be more efficient when using plant biomass grown in the spring sowing period.

The study of the indicators of accumulation of the main nutrients in the formed biomass of oilseed radish is comparable to their concentration noted in Tables 3.8–3.10. The average long-term ratio of content and accumulation in the aboveground biomass of N:P:K:Ca:S was established in the following expression (with indication of the range of values) 1.00(0.65–1.59):0.24(0.18–0.40):1.39(1.04–2.05):0.38(0.28–0.56):0.16(0.14–0.19) for spring sowing and 1.00 (0.51–1.39):0.20 (0.11–0.25):1.21 (0.70–1.70):0.31(0.21–0.42):(0.70–1.70):0.31(0.21–0.42):0.15(0.10–0.21) for the summer sowing period. To compare the intensity of accumulation of individual elements for different mustard species 0.8–1.2:0.3–0.6:1.2–1.6: 0.40–0.65:0.24–0.60 for other types of cruciferous plants used in the system of intermediate green manure use (for example, Barbarea vulgaris L.) – 0.6–1.1:0.2–0.6:1.1–1.3:0.25–0.50:0.18–0.32. That is, oilseed radish is characterized by similar features in the accumulation of basic nutrients as for widely used rapeseed and mustard in the MSCC system. Based on the determined ratios, the intensity of growth processes for the formation of oilseed radish leaf mass will be predicted to be high with sufficient soil supply of available forms of nitrogen and potassium. As for phosphorus, according to the findings of Weih et al. (2018), at a low level of accumulation of the element, the critical period in relation to the need for it shifts to the early stages of the growing season. At the same time, in terms of the direction and use of 'catch crop' in the MSCC system, according to the ‘N uptake’ indicator, oilseed radish showed significantly lower levels of nitrogen removal over the ten-year evaluation period compared to the predicted levels of this indicator for already noted widely used crops such as rapeseed and mustard. The determined nature of accumulation also showed a high positive response of oilseed radish to additional mineral nutrition, especially during the period of active growth of vegetative mass, which according to our studies corresponds to 30-35 days after sowing for spring and 25 days after sowing for summer sowing (Figure 3.4). According to the accumulation of phosphorus and calcium in comparison with niche cruciferous crops, oilseed radish is classified as a species with intensive accumulation of these elements (based on the gradation assessment of Wallace & Mueller, 1980). Based on the above, the established high levels of productivity of oilseed radish at lower levels of consumption of the main elements to ensure this productivity allow us to recommend it for the system of saturating multi-term crops in the links of typical crop rotations with the criterion of ‘catch crop’ and ‘green manure’. This statement is consistent with the findings of Grzebisz et al. (2022, 2023). This is also confirmed by the results of equivalent transformation of the formed aboveground mass of oilseed radish in terms of the content of organic and dry matter in cattle manure. Such conversion, which provided an average perennial rate of more than 20 tons per hectare and taking into account the study by Carr et al. (2020), proved the effectiveness of using oilseed radish at both sowing dates in the system of bioorganic fertilization technologies and rehabilitation of degraded soils with the direct use of green manure.

It is important to note that the characterized basic indicators and correlations (according to Ramírez-García et al. (2015)) that determine the belonging to different niche areas in the MSCC system for oilseed radish formed a regression system of dependencies (the most significant of which) are presented in Table 6. According to the regression equations, it was found that the quality of plant residues (RQ) decreased with both an increase in precipitation and an increase in temperature. This is explained by the intensification of vegetative growth processes with a slowdown in qualitative biochemical transformations characteristic of natural physiological aging. At the same time, an increase in temperature will ensure an increase in the content of lignin derivatives and an increase in precipitation will cause a general decrease in the components of NDF and ADL (this is consistent with the similar nature of the regression relationships for the indicative indicator of fiber content (CFb)). In interaction, this will form plant residues with rapid rates of aerobic decay and reduce their quality in terms of bio-cycling of their components. This character is consistent with the determined dependencies between RQ and hydrothermal ratios – the aridity coefficient I_{DM} and the moisture coefficient K_h and is confirmed by the analysis in Bajgai et al. (2014).

The C/N ratio also decreased with an increase in both precipitation and average daily temperature. This is due to the already mentioned theory of stress proteins and an increase in the content of nitrogenous compounds, and in the case of precipitation due to the extension of the growing season and a decrease in the rate of physiological aging with the formation of an increased nitrogen content in late phenostages.

In the case of temperature, a stress response system is formed in the form of an increased content of stress proteins and, accordingly, a higher concentration of nitrogen in biomass. Against the background of the previously mentioned stable organic carbon content, this ultimately reduces the value of the C/N ratio. At the same time, the negative forming direction in the equation of the aridity index (I_{DM}) and the positive forming direction for the moisture coefficient (K_h) indicates a more important role of the precipitation to evapotranspiration ratio than precipitation to the sum of temperatures. In the first case, this contributes to the accumulation of both organic carbon and nitrogen compounds and is consistent with the estimates of Agren & Weih (2012) and is confirmed by the presented results of regression dependencies on the resultant component Nupt. For the indicator of soil coverage ‘GC’, the peculiarities of the formation of the indicator for oilseed radish were confirmed: an increase in its value with an increase in precipitation and a decrease in evaporation in terms of the value of the moisture coefficient (K_h) and a decrease in the average daily air temperature. This is consistent with all the dependencies that determine the intensity of growth processes and the analysis of the formation of the indicator in the dynamics (Figure 3.3) and with the conclusions of a number of studies (Ramirez-Garcia et al., 2012; Ugrenović et al., 2019; Kashyap et al., 2023).

Table 3.10

Multiple regression dependence between hydrothermal conditions of vegetation and indicators of value of vegetative mass of oilseed radish according to the criteria of multi-service cover crop (MSCC) (average data for 2014–2023) (based on the results of the author’s own research)

Qualitative indicator	Equation of dependence	Parameters of the equation		Statistical evaluation of components				
		x	y	Multiple R	Multiple $R^2_{(adj.)}$	F	df1, df2	*p*
RQ	RQ = 92.503-0.00995x-0.4975y	Precipitation (mm)	Average daily temperature (°C)	0.873	0.735	27.334	2.170	*<0.001*
C/N	C/N = 24.5149-0.0189x-0.4478y			0.788	0.576	13.891	2.170	*<0.001*
N_{upt}	N_{upt} = -7.040+0.1394x+1.3556y			0.850	0.689	22.058	2.170	*<0.001*
CFb	CFb = 21.851-0.0152x-0.1937y			0.862	0.713	24.599	2.170	*<0.001*
GC	GC = 84.205+0.0934x-1.343y			0.821	0.636	17.625	2.170	*<0.001*
GSL	GSL = 12.918-0.0147x+0.1731y			0.806	0.609	15.773	2.170	*<0.001*
RQ	RQ = 84.268-1.5649x+10.285y	I_{DM}	K_h	0.738	0.545	10.188	2.170	*<0.05*
C/N	C/N = 17.569-2.151x+13.344y			0.854	0.729	22.823	2.170	<0.001
N_{upt}	N_{upt} = 13.420+9.622x-54.875y			0.921	0.831	47.785	2.170	*<0.001*
CFb	CFb = 25.222-0.1074x-0.7081y			0.815	0.625	16.785	2.170	*<0.001*
GC	GC = 62.557-1.1471x+16.155y			0.895	0.707	21.789	2.170	*<0.001*
GSL	GSL = 15.779-0.0079x-1.2605y			0.783	0.612	19.446	2.170	<0.001

The regression analysis proved a positive formative effect of the increase in average daily temperatures and a negative formative effect of precipitation on the accumulation of glucosinolates (GSL), which is consistent with a significantly higher concentration of them in the biomass of oilseed radish during the summer sowing period, especially under conditions of moisture deficit against the background of intensively increasing average daily temperatures and positively correlates with similar studies on other cruciferous crops (Milford & Evans, 1991; del Carmen Martínez-Ballesta et al., 2013, Bellec et al., 2023; Ben Ammar et al., 2023).

An important component in assessing the belonging of oilseed radish to the MSCC system is an attribute assessment of the component coefficients of the resulting equations of the corresponding conceptual direction of use. For scientific detailing and substantiation of the selected attributes, a scientific systematization of a number of studies that directly or indirectly relate to the issues of MSCC formation was applied. The results of this generalization in terms of the coefficients of the equations in accordance with the fundamental scale (Saaty & Vargas, 2012) and the resulting direction of formation of the selected method of use by sign at the attribute coefficient are presented in Table 7.

To update the analysis for the direction of use 'fodder crop', the fiber content indicator (CFb) was replaced by the indicator 'dietary fiber content' (DFb) in accordance with the feed assessment system (FOSS. 2018). The formed array of initial data on the importance of the studied attributes in the formation of the direction of use of oilseed radish allowed us to obtain their normalized matrix (Table 3.11–3.13).

Accordingly, the conditions of 2014 and 2023 were recognized as ensuring the maximum realization of the possibility of multicomponent use of aboveground biomass of oilseed radish in all defined areas. In contrast, the conditions of 2015 and 2017 had a significant lowest level of criterion realization. In the system of evaluation of individual attributes, their importance was confirmed on the basis of the systematization of the results of long-term studies, according to which the indicator of the amount of formed aboveground biomass is dominant in the context of all studied areas of use of oilseed radish, and the fiber content or its dietary form is in the last ranking place. At the same time, the significance of the difference within the years of evaluation was minimal for the attributes 'GSL', 'CFb' and 'RQ', which is associated with the different directions of the identified trends of their formation for different uses in the MSCC system and is positively consistent with the data of Ramírez-García et al. As a result, the results of the multicriteria analysis within different sowing dates established the final sums of normalized and weight-adjusted attributes (Table 3.12). Accordingly, it was determined that different sowing dates of oilseed radish have different years of optimality for a particular use. The maximum number of maximum values of the adjusted coefficients was observed for the conditions of 2019 for the spring sowing period and for the conditions of 2022 for the summer sowing period. On this basis and based on the research of Ramirez-Garcia et al. (2015), El Amine et al. (2016), the possibility of involving oilseed radish as an effective candidate for crops of the MSCC system was determined. The sowing dates influenced the assessment of the efficiency of use, which is confirmed by the average normalized index for this attribute in the array of years of study. Shifting the sowing dates of oilseed radish from spring to summer increased the efficiency of its use in the such criterion area as ‘Green manure’, ‘Fodder’ and ‘Catch crop’ (increase in the rating position by 1–2 levels).

Table 3.11

Intensity of importance of the normalized attributes on fundamental scale in oilseed radish as the multi-service cover crop (MSCC) utility functions assigned by the decision makers based on analysis of publications for both sowing dates (based on the results of the author’s own research)

Use	**GC***	**BM**	**C/N**	**N_{upt}**	**RQ**	**GSL**	**CFb**	**Attributes selected based on the analysis of publications**
1	2	3	4	5	6	7	8	9
Cover crop	5	2	1	1	3	3	1	Snapp et al., 2005; Clark, 2008; Bodner et al., 2010; Tixier et al., 2010; Bangarwa et al., 2011; Zachariah, 2011; Justes et al., 2012; Gieske, 2013; Ramírez-García et al., 2015a; White et al., 2016; Wendling et al., 2016; Wollford & Jarvis, 2017; Warren, 2017; Couedel et al., 2018, 2019; Tribouillois et al., 2018; Bhogal et al., 2019; Toom et al., 2019; Ugrenović et al., 2019; Chapagain et al., 2020; Duff et al., 2020; Norberg & Aronsson, 2020; Hansen et al., 2021; Lövgren, 2022; Quintarelli et al., 2022; Ait Kaci Ahmed et al., 2022; Restovich et al., 2022
	**+	+	+	-	+	+	+	

(End of Table 2.36)

1	2	3	4	5	6	7	8	9
Catch crop	2	2	1	2	2	3	1	Snapp et al., 2005; Molinuevo-Salces et al., 2014; Gieske, 2013; Alonso-Ayuso et al., 2014; Ramírez-García et al., 2015, 2015a; White et al., 2016; Wendling et al., 2016; Wollford & Jarvis, 2017; Warren, 2017; Couedel et al., 2018, 2019; Bhogal et al., 2019; Sieling et al., 2019; Toom et al., 2019; Chapagain et al., 2020; Duff et al., 2020; Hansen et al., 2021; Lövgren, 2022; Restovich et al., 2022
	+	+	-	-	+	+	+	
Green manure	3	5	2	3	5	7	3	Kirkegaard & Sarwar, 1998; Eberlein et al., 1998; Gimsing & Kirkegaard, 2006; Clark, 2008; Florentín, 2010; Bangarwa et al., 2011; Zachariah, 2011; Ramírez-García et al., 2015; Flores-Sánchez et al., 2016; Stubbs & Kennedy, 2017; Galaup, 2018; Hu et al., 2018; Heuermann et a., 2019; Li et al., 2019; Liu et al., 2020; Salume et al., 2020; Lövgren, 2022; Ait Kaci Ahmed et al., 2022; Lei et al., 2022; Jie, 2022; Jauhiainen, 2022; Wang et al., 2022; Israt & Parimal, 2023; Källén, 2023;
	+	+	-	-	+	+	-	
Fodder	3	5	3	3	1	7	5	Gustine & Jung, 1985; Capecka & Libik, 1998; Westwood & Mulcock, 2012; Ramírez-García et al., 2015, 2015a; Winkler, 2017; FOSS. 2018; Duff et al., 2020; Kılıç et al., 2021; Olofsson & Ernfors, 2022; Abdelrahman et al., 2022; Safaei et al., 2022; Jie, 2022; Ţiţei, 2022
	+	+	-	+	+	-	+	
Biogas	3	5	5	3	5	5	3	Cleemput, 2011; Herout et al., 2011; Murphy et al., 2011; Carvalho et al., 2011; Herrmann et al., 2011, 2014; Al Seadi et al., 2013; Molinuevo-Salces et al., 2013; Dandikas et al., 2014; Guarino et al., 2016; Herrmann et al., 2016; Einarsson & Persson, 2017; Maier et al., 2017; Martínez-Gutiérrez, 2018; Cerón-Vivas et al., 2019; Choi et al., 2020; Liu et al., 2020; Oliveira et al., 2021; Launay et al., 2022; Jauhiainen, 2022; Fajobi et al., 2023; Lallement et al., 2023; Lymperatou et al., 2023; Manyi-Lohn & Lues, 2023; Shitophyta et al., 2023
	+	+	+	+	+	-	-	

Equations with attribute for uses (desirable trend of formation: growth '+', decline '-')	
Cover crop	$5GC + 2BM + C/N - N_{upt} + 3RQ + 3GSL + CFb$
Catch crop	$2GC + 2BM - C/N - 2N_{upt} + 2RQ + 3GSL + CFb$
Green manure	$3GC + 5BM - 2C/N - 3N_{upt} + 5RQ + 7GSL - 3CFb$
Fodder	$3GC + 5BM - 3C/N + 3N_{upt} + RQ - 7GSL + 5DFb^{***}$
Biogas	$3GC + 5BM + 5C/N + 3N_{upt} + 5RQ - 5GSL - 4CFb$

[*]GC: ground cover (% на 60 добу після сівби); BM: biomass reached at the end of the experiment (kg m^{-2}); CN: C/N ratio; N_{upt}: N uptake (g m^{-2}); RQ: residue quality (g kg^{-1}_{DM}); CFb: fiber content (g kg^{-1}_{DM}); DFb: dietary fibre content (g kg^{-1}_{DM}); GSL: glucosinolate productivity (mmol m^{-2}). [**]desirable trend of formation: growth '+', decline '-' [***]DFb only for the 'fodder crop' direction.

Table 3.12

Average of normalized values for 7 attributes of oilseed radish evaluation as multi-service cover crop functions (MSCC), 2014–2023 (averaged for the complete data set, directions of use–sowing dates) (based on the results of the author's own research)

Year	GC*	BM	C/N	N_{upt}	RQ	GSL	CFb (DFb**)	Amount	Rating
2014	0.213^{a}	0.268^{b}	0.129^{c}	0.069^{b}	0.072^{b}	0.086^{b}	0.057^{c}	0.897	1
2015	0.128^{f}	0.196^{h}	0.118^{e}	0.064^{d}	0.075^{a}	0.089^{a}	0.061^{b}	0.730	9
2016	0.179^{c}	0.231^{e}	0.120^{e}	0.069^{b}	0.075^{a}	0.088^{a}	0.062^{a}	0.824	6
2017	0.151^{h}	0.208^{g}	0.123^{d}	0.070^{b}	0.076^{a}	0.089^{a}	0.064^{a}	0.782	8
2018	0.154^{g}	0.214^{f}	0.125^{d}	0.075^{a}	0.075^{a}	0.089^{a}	0.064^{a}	0.796	7
2019	0.168^{e}	0.278^{a}	0.136^{a}	0.067^{c}	0.073^{b}	0.088^{a}	0.057^{c}	0.868	3
2020	0.167^{e}	0.262^{c}	0.120^{e}	0.063^{d}	0.074^{a}	0.088^{a}	0.060^{b}	0.834	5
2021	0.159^{f}	0.263^{c}	0.117^{f}	0.069^{b}	0.076^{a}	0.089^{a}	0.060^{b}	0.834	5
2022	0.172^{d}	0.270^{b}	0.127^{c}	0.073^{a}	0.076^{a}	0.088^{a}	0.061^{b}	0.867	4
2023	0.185^{b}	0.262^{c}	0.132^{b}	0.071^{b}	0.076^{a}	0.088^{a}	0.060^{b}	0.873	2
Average	0.168	0.245^{d}	0.125^{d}	0.069^{b}	0.075^{a}	0.088^{a}	0.061^{b}	–	–
Rating	2	1	3	6	5	4	7	–	–

* GC: ground cover (% at 60 days after sowing); BM: biomass reached at the end of the experiment (kg m^{-2}); CN: C/N ratio; N_{upt}: N uptake (g m^{-2}); RQ: residue quality (g $kg^{-1}{}_{DM}$); CFb: fiber content (g $kg^{-1}{}_{DM}$); DFb: dietary fibre content (g $kg^{-1}{}_{DM}$); GSL: glucosinolate productivity (mmol m^{-2}). **DFb for the direction use only for 'fodder crop' direction.

At the same time, the positions in the criterion of 'Biogas' use remained unchanged. However, the direction of its use in the direction of 'Cover crop' is significantly lower (decrease in the rating by 4 positions). Such changes, taking into account the saturating and intermediate nature of the summer sowing of oilseed radish, prove the technological potential of its use in a wide period of time in the MSCC system. It was also found that the rating by the direction of use depended on the conditions of the year. For example, for the conditions of 2018 and 2023, the direction 'Biogas' during the summer sowing period had the first rating among other directions of use with an average fourth position in the consolidated data set. Similar trends were found for other uses. This confirms our conclusions about the role of hydrothermal regimes of the growing season in shaping compliance with MSCC criteria.

Table 3.13

Sum of normalized values multiplied by the weighting coefficients for 7 attributes attained by each use oilseed radish as multi-service cover crop functions (MSCC), 2014–2023 (based on the results of the author's own research)

Year of research	Direction of use in the concept of MSCC										Rating by MSCC
	Cover crop		Catch crop		Green manure		Fodder		Biogas		
	*SprS	SumS	SprS	SumS	SprS	SumS	SprS	SumS	SprS	SumS	
2014	0.82^{d}	0.86^{b}	0.95^{b}	0.85^{d}	0.88^{b}	0.91^{c}	0.96^{b}	0.91^{c}	0.95^{b}	0.88^{c}	1
2015	0.82^{d}	0.84^{c}	0.73^{g}	*0.72f*	*0.75^{f}*	*0.62^{h}*	0.76^{g}	*0.60^{g}*	0.75^{g}	*0.59^{g}*	10
2016	0.83^{d}	0.82^{d}	0.76^{d}	0.83^{e}	0.80^{e}	0.89^{d}	0.79^{f}	0.89^{c}	0.78^{f}	0.87^{c}	7
2017	0.82^{d}	*0.73^{g}*	0.68^{h}	0.83^{e}	0.80^{e}	0.87^{e}	*0.65^{i}*	0.87^{d}	*0.65^{i}*	0.87^{c}	9
2018	0.83^{d}	0.79^{e}	*0.63^{i}*	0.87^{c}	0.80^{e}	0.89^{d}	0.70^{h}	0.88^{c}	0.69^{h}	0.93^{b}	8
2019	*0.79^{e}*	**0.89^{a}**	**0.98^{a}**	0.82^{e}	**0.91^{a}**	0.76^{g}	**0.99^{a}**	0.73^{f}	**0.99^{a}**	0.72^{f}	4
2020	0.87^{b}	0.78^{f}	0.86^{c}	0.82^{e}	0.85^{c}	0.79^{f}	0.90^{c}	0.80^{e}	0.90^{c}	0.76^{e}	6
2021	**0.93^{a}**	0.84^{c}	0.74^{g}	0.86^{d}	0.82^{d}	0.87^{e}	0.80^{e}	0.87^{d}	0.80^{e}	0.85^{d}	5
2022	0.85^{c}	0.80^{e}	0.77^{f}	0.90^{b}	0.83^{d}	**0.99^{a}**	0.82^{e}	**0.99^{a}**	0.81^{e}	**0.98^{a}**	3
2023	0.82^{d}	0.81^{d}	0.84^{c}	**0.93^{a}**	0.85^{c}	0.93^{b}	0.88^{d}	0.94^{b}	0.87^{d}	0.94^{b}	2
Average	0.838^{a}		0.794^{d}		0.829^{b}		0.825^{b}		0.819^{c}		–
		0.816^{d}		0.843^{b}		0.852^{a}		0.849^{a}		0.839^{b}	–
Rating by use	1		5		2		3		4		–
		5		3		1		2		4	–
Consistensy index (CI)*	0.431		0.188		0.340		0.370		0.226		–
		0.244		0.357		0.415		0.407		0.305	

*SprS – Spring sowing; SumS – Summer sowing. In bold, the maximum values, and in italics, the minimum. Case letters indicate statistical differences ($p < 0.05$); *the indicator is a component of the scheme of Analytic Hierarchy Process (AHP) according to Saaty & Vargas (2012).

According to the results of a multi-year study cycle, oilseed radish showed high productivity and adaptability. This is confirmed by the average indicators of its long-term productive and biochemical portfolio, which for the spring sowing period had the following parameters: formed aboveground biomass (BM) 24.04 t ha^{-1}, formed root biomass (RBM) 8.7 t ha^{-1}, soil coverage index on the 70th day after sowing (GC_{70}) 73.77%, crude protein content (CP) 15.56%$_{DM}$, crude fat (CF) 3.98%$_{DM}$, cellulose 21.73%$_{DM}$, hemicellulose 10.95%$_{DM}$, phosphorus 0.62%$_{DM}$, potassium 3.63%$_{DM}$, calcium 0.96%$_{DM}$, sulfur 0.42%$_{DM}$, glucosinolates (GSL) 13.57 μmol g^{-1} DM, C/N ratio 16.02, Residue quality (RQ) 84.99%$_{DM}$, Carbohydrates (CH) 67.08%$_{DM}$, GSL productivity 41.2 mol ha^{-1}. For the summer sowing period, similar parameters were as follows: BM 18.34 t ha^{-1}, RBM 5.50 t ha^{-1}, GC_{70} 50.74%, CP 19.16%$_{DM}$, CF 4.61%$_{DM}$, cellulose 24.43 %$_{DM}$, hemicellulose 12.85%$_{DM}$, phosphorus 0.63%$_{DM}$, potassium 3.96%$_{DM}$, calcium 1.01%$_{DM}$, sulfur 0.48%$_{DM}$, GSL 19.70 μmol g^{-1} DM, C/N ratio 13.30, Residue quality (RQ) 81.03%$_{DM}$, CH 61.93%$_{DM}$, GSL productivity 54.90 mol ha^{-1}.

Using the above data block with the application of Multi-criteria decision aiding (MCDA), the possibility of multi-purpose use of oilseed radish in the criterion system of multi-service cover crop (MSCC) was proved in the following order of decreasing technological significance for the conditions of unstable hydrothermal regime of its vegetation period on soils with an average level of soil fertility potential (averaged for both sowing dates): ‘Green manure’ – ‘Fodder’ – ‘Cover crop’ – ‘Biogas’ – ‘Catch crop’.

3.2. Potential of oilseed radish as a green manure crop

It is noted (Gadzalo, 2016) that the choice of green manure form is determined by the soil, climatic and economic conditions of the agricultural producer (Figure 3.5).

The forms of green manure are determined by the choice of the method of sowing or underplanting green manure crops. The following forms of green manure are distinguished:

– basic (independent) – involves the use of perennial and annual grasses for green fertilizer and the replacement of black manure with green manure. The fallow crops are sown in the fall or spring using the entire green mass as fertilizer, and if necessary, the flocks;

– Sowing – green manure seeds are sown along the rows immediately after sowing the cover crop. After the main crop is harvested, green manure is built up on a high cut, which is plowed under the next crop;

– intermediate green manure is divided into stubble and stubble;

– pre-harvest green manure is carried out in the first half of the growing season after the field is cleared of annual grasses or corn for silage;

– post-harvest green manure is carried out in the second half of the growing season after harvesting early grain crops – winter crops, barley; early vegetables – radishes, early cabbage, early cucumbers, etc.

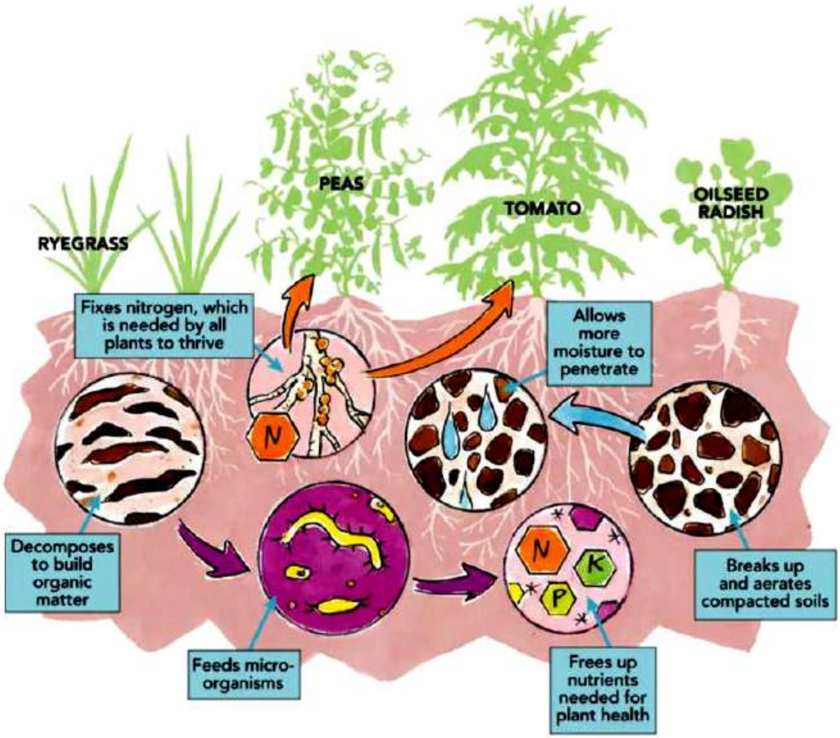


Figure 3.5 – Positive aspects of green manure in the soil

Independent and flock green manure. Traditionally, an independent form of green manure in the form of flocks of annual and perennial grasses is available for farms in any soil and climatic zone of Ukraine if they grow perennial and annual grasses that can grow green mass by the end of the growing season. This form of green manure is most promising for areas of unstable and insufficient moisture.

It is generally accepted that green manure fallowing is most appropriate as a temporary measure on infertile, depleted sandy soils, especially those remote from farms. Due to changing climatic conditions and increased rainy periods in areas of unstable moisture, green manure is being introduced to the Left Bank Forest-Steppe and southern Ukraine, not only on irrigated lands but also on rainfed lands.

Post-cutting green manure. Post-cutting green manure is carried out immediately after harvesting the main crop – winter or annual grasses and corn for green fodder. Post-harvest crops accumulate more green mass due to the long duration of the growing season. The green mass is used for winter cereals and spring row crops such as potatoes, corn, sugar beets and fodder.

Crops from the cruciferous family, such as oil radish, spring rape, percoche, and legumes such as lupine, sweet clover, and seradella, are effective for post-mowing green manure. For sowing, the field is cultivated immediately after it is freed from the main crop. With the gradual harvesting of green mass for fodder, the field is then cultivated with a heavy disk harrow or shallow plowing.

Intermediate green manure. Intermediate green manure can be either post-mowing or post-harvest, depending on the timing of sowing. This is the most common method of green manure, especially in areas of sufficient moisture and on irrigated land.

Features of growing crops for green manure in intercrops:

1. After harvesting the predecessor (mainly cereal spiked crops), the field is immediately (to prevent moisture evaporation from the soil) disked in two tracks, followed by leveling and rolling with any combined unit such as “Europak”. It is advisable to leave high stubble or straw chopped during harvesting on the field.

2. When growing cruciferous and cereal crops (oil radish, winter rye and others) for green manure, it is recommended to apply nitrogen fertilizers in the rate of N30-45 for regenerative agriculture. When growing legumes on green manure, no fertilizer is required.

3. Seeding rates should be calculated 25–30% higher than those recommended for technologies of growing crops for economic needs.

4. It is necessary to carry out post-sowing rolling.

5. When growing green manure, all phosphorus and potassium fertilizers and half of the nitrogen fertilizers intended for the main crop should be

applied under “pioneer plants” (green fertilizers); this makes it possible to increase the return on mineral fertilizers by 1.5-2 times.

6. When applying manure in crop rotation, it is advisable to combine it with green manure cultivation, which will increase the aboveground and root mass of green manure by 2–3 times, reduce the loss of nutrients from manure by 2–2.5 times, and, accordingly, increase the coefficient of organic fertilizer use by 1.6–1.8 times.

7. The mass of intermediate green manure crops is incorporated into the soil with one pass of disks (October-November); with high and dense grass (yield over 35 t/ha) – with two passes.

8. Pre-sowing tillage for the following early spring crops consists of harrowing (which levels the surface) and rolling. The soil surface remains lumpy after the autumn disk harrowing of green mass. Snow is well retained on it, which ensures the emergence of full sprouts 3–4 days after sowing.

9. Early incorporation of a large mass of green fertilizer into the soil in the intermediate sowing can have a negative impact on the yield of the subsequent crop. In this case, fresh organic matter is intensively mineralized and there are significant losses of nitrogen and humus. Therefore, it is advisable to plow green manure in late fall, and for spring crops in spring. Sowing is carried out with a seeder with disc coulters equipped with furrows.

Post-harvest green manure is the most common form of green manure due to the sufficient amount of vacant land after harvesting early crops. The effectiveness of growing post-harvest green manure depends on the efficiency of agrotechnical work immediately after harvesting the predecessor, clearing the field of straw or after shredding it and applying and cultivating the soil to obtain friendly and complete green manure emergence. For this purpose, soil cultivation is carried out with a BDT-7 disk harrow with harrowing with a BIG-3 needle harrow or other tools at an increased speed and rolling on soils of medium and heavy granulometric composition. With sufficient moisture, the green manure seeds are sown into the stubble, followed by disking to a depth of 6–8 cm. Resource- and moisture-saving surface tillage is highly effective, reducing the time required to prepare the soil for sowing.

For post-harvest green manure of cruciferous crops such as oilseed radish, spring and winter rape, and rape, it is advisable to apply nitrogen fertilizers at the rate of 60–90 kg/ha for regenerative agriculture, as the soil reserves of assimilable nitrogen compounds are sharply reduced at the time of sowing. In the Polissya, Northern and Western Forest-Steppe regions, mustard, oil radish, fodder cabbage, and rapeseed are sown no later than August 5–10. At the end of July, lupine, peas, oats, vetch and their mixtures are sown. It is important to note that high-quality seeds of large fractions are chosen for green manure. The preferred methods of sowing are conventional row or narrow-row, or scattered sowing. In case of late sowing, the seeds are planted by shallow disking, with a seeding depth of 2–3 cm.

Ushkarenko et al. (2000) note that cruciferous crops are characterized by a short growing season, high cold resistance, and the presence of high protein content in the green mass. Being good predecessors for all crops in the crop rotation, cabbage crops leave 120–200 c/ha of crop residues in the soil, which are quickly mineralized, improve the mechanical composition and fertility of the soil (Table 3.14).

Table 3.14

Yield of green mass of cabbage crops depending on the nutritional background, c/ha

Growing crops	Nutrition background	Research periods			Ave-rage	Dry matter harvest, c/ha
		1998	1999	2000		
Camelina	No fertilizers	96	118	107	107	21.9
	$N_{60}P_{45}$	186	228	192	202	47.9
	$N_{120}P_{90}$	254	246	251	250	51.2
White mustard	No fertilizers	137	208	190	178	37.7
	$N_{60}P_{45}$	279	302	265	282	64.3
	$N_{120}P_{90}$	311	369	292	324	59.0
Rapeseed	No fertilizers	177	252	219	216	40.8
	$N_{60}P_{45}$	360	334	305	333	67.9
	$N_{120}P_{90}$	445	370	372	396	70.9
Oilseed radish	No fertilizers	256	252	220	243	33.0
	$N_{60}P_{45}$	460	371	336	389	40.3
	$N_{120}P_{90}$	533	422	390	448	59.1

LSD_{05}, c/ha: for culture 30.7 21.8 18.5; for the power supply background 26.6 19.0 16.0; for the interaction of factors 53.1 37.9 32.0

When growing cabbage crops, the soil was enriched with organic matter due to their root system by 22.2–45.5 c/ha.

As a result of the research by Ushkarenko et al. (2000), the following conclusions were made:

1. The highest yield of green mass was provided by oil radish on all nutrition backgrounds.

2. The maximum dry matter yield (67.9–70.9 c/ha) was obtained when growing oilseed rape with fertilizers in doses of $N_{60}P_{45}$ and $N_{120}P_{90}$.

3. The lowest coefficient of water consumption (61–106 m^3/t) was recorded on all nutrition backgrounds in oilseed radish.

In another study (Hansen et al., 2020) six different species of green manure, white lupin (Lupinus albus), winter vetch (*Vicia villosa*), crimson clover (*Trifolium incarnatum*), buckwheat (*Fagopyrum esculentum*), oilseed radish (*Raphanus sativus*) and winter rye (*Secale cereale*)) were sown after harvest of oilseed rape in plots with either low or moderate soil fertility with 6 and 16 mg Olsen-P kg $soil^{-1}$, respectively. According to the results of the research, oil radish demonstrated high efficiency and biological and agrochemical productivity in comparison with other green manure crops studied (Figures 3.6–3.8).

Figure 3.6 – Biomass sampling in autumn revealed that biomass production of winter vetch, crimson clover, oilseed radish and winter rye were significantly decreased when growing at low soil fertility whereas white lupin and buckwheat showed the same growth at both fertility levels

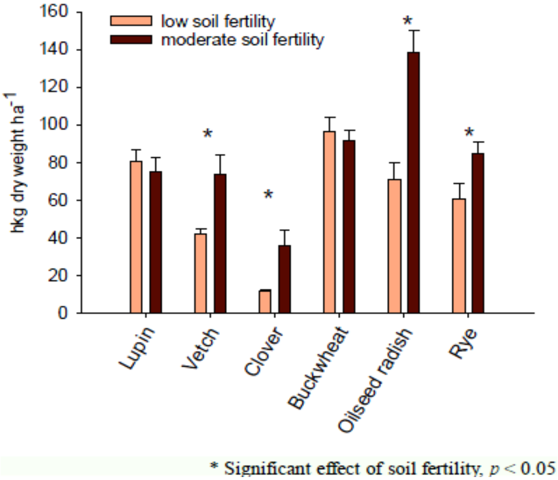


Figure 3.7 – After 80 days of incubation, the treatments receiving sorrel and oil seed radish revealed the highest P mobilization, with an increase of water-extractable P (WEP) corresponding to 50 and 31%, respectively, of the added P.

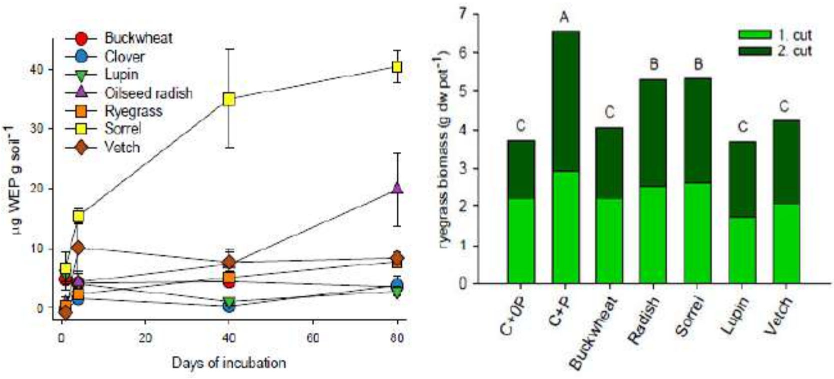


Figure 3.8 – After 40 days of ryegrass growth, the addition of oilseed radish and sorrel significantly increased the growth of ryegrass by 43 and 44 % compared to the 0P control, respectively, confirming their value as green manure plants for crop P nutrition

In general, according to the results of long-term studies, oil radish is included in the list of cover crops for different soil and climatic zones of the USA and Canada (Table 3.15).

Table 3.15

Cover crops/green manures at various planting times

Early Spring	Early Summer	Early autumn
Buckwheat	Buckwheat	Buckwheat
Canola (Rapeseed)	Canola (Rapeseed)	Canola (Rapeseed)
Red, white or crimson clover	Red, white or crimson clover	Red, white or crimson clover
Oilseed Radish	Oilseed Radish	Oilseed Radish
Mustards	Mustards	Mustards
Daikon Radish	Daikon Radish	Daikon Radish
Spring cereal crops	Hairy Vetch	Hairy Vetch
Austrian winter pea	Chickling Vetch	Winter cereal crops
Austrian Winter Pea/cereal	Sorghum	Austrian Winter Pea
Purple Top Turnips	Sorghum Sudangrass	Austrian Winter Pea/cereal
	Teff	Purple Top Turnips
	Pearl Millet	
	Spring Peas	
	Oats	

The research by Kemper et al. (2020) noted that in mixtures, oilseed radish was dominant in shoot and root underlining the importance of species identity in cover crop mixtures. Positive mixture effects for RLD and RMD were more frequent in the subsoil due to a strong rooting of oil radish if integrated as a mixture partner. Consistently positive mixture effects were found for SRL, i.e. mixing makes roots thinner. Root mass complementarity, vertical root niche differentiation and mixture effects in topsoil might have not occurred pronouncedly because partners were not sufficiently balanced in mixtures. Thus, future research should focus on the balance when mixing different cover crop species. More conceptual planning of seed density ratios and mixture composition is advised to design well-balanced cover crop mixtures to exploit mixture effects above and belowground more effectively. Mixture effects seem to be more prominent for morphological than architectural root traits. Enhanced SRL in mixtures might be linked to higher root turnover and rhizodeposition which would influence cover crop functions such as carbon storage and microbial activity. Future research on roots of cover crop mixtures should consider root turnover, rhizodeposition, microbial processes as well as other acquisitive root traits such as root tips, branching and root N content (Figure 3.9–3.11).

Kemper et al. (2020) have given first insights into belowground interactions of mixed cover crops and mixture effects on their root traits in autumn. Future root research will profit from methods that allow an understanding of belowground interaction throughout the crop growth period.

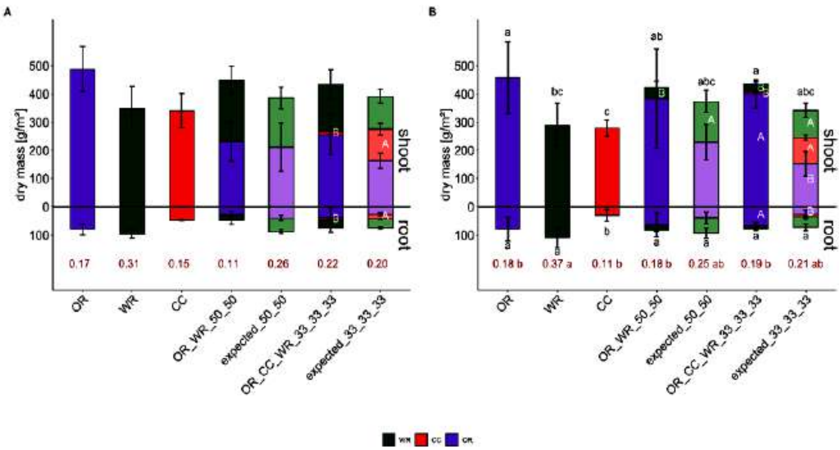


Figure 3.9 – Mean values ± standard deviation of shoot (n = 4) and root (n = 3) dry mass [g/m2] and mean values of root-shoot-ratio (n = 3) of sole cover crops oil radish (OR), winter rye (WR), crimson clover (CC), 50:50 cover crop mixtures of oil radish and winter rye (0R_WR_50_50), 33:33:33 cover crop mixtures of oil radish, crimson clover and winter rye (0R_ CC_WR_33_33_33) and of expected mixtures (corresponding proportions of sole crops) in 2018 (A) and 2019 (B). Bars above 0 represent shoot dry mass, bars below 0 show root dry (Kemper et al., 2020)

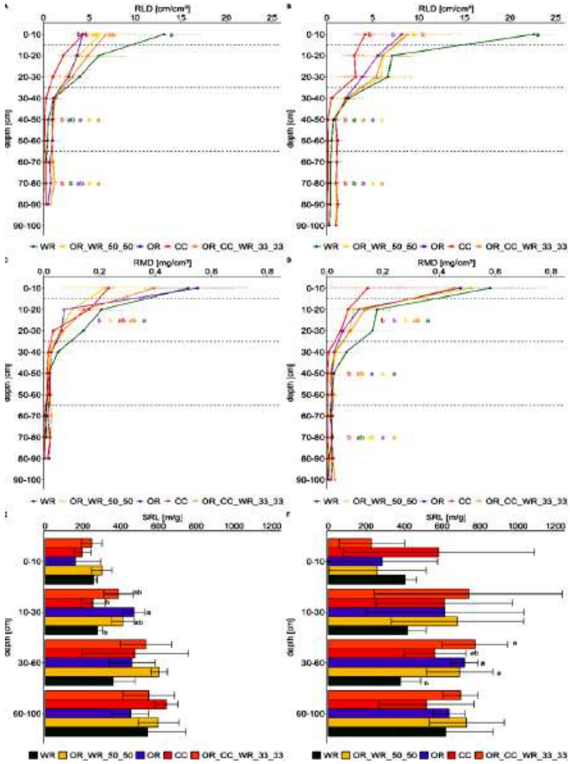


Figure 3.10 – Mean values ± standard deviation (n = 3) of root length density [cm/cm3] (RLD) (A, B), root mass density [mg/cm3] (RMD) (C, D) and specific root length [m/g] (SRL) (E, F) of sole cover crops oil radish (OR), winter rye (WR), crimson clover (CC), 50:50-cover crop mixtures of radish and rye (OR_WR_50_50), 33:33:33-cover crop mixtures of radish and rye (OR_CC_WR_33_33_33) in 2018 (A, C, E) and 2019 (B, D, F) at different soil depth levels. Colours refer to cover crops: green for rye, yellow for 50:50-mixture, orange for 33:33:33-mixture, red for clover and violet for radish. Different lowercase letters indicate significant differences (p < 0.05, HSD Tukey-test) between different cover crops within the different soil depth layers (0-10 cm, 10-30 cm, 30-60 cm and 60-100 cm) within one year (Kemper et al., 2020)

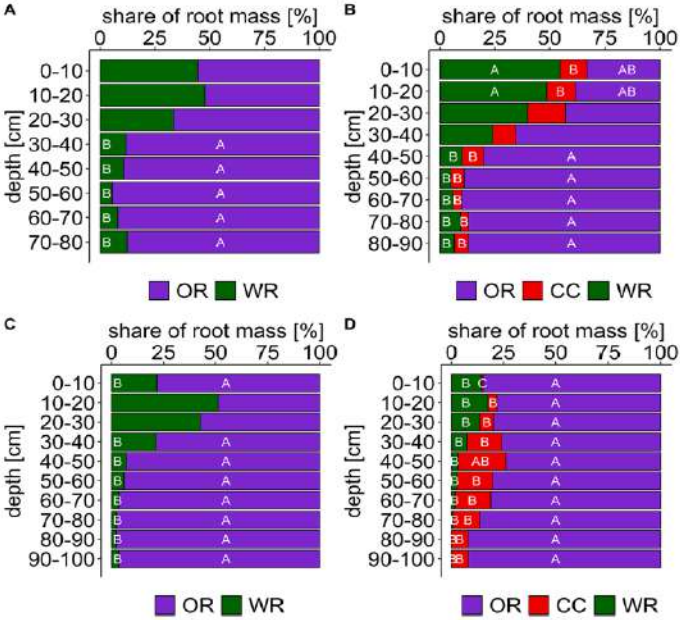


Figure 3.11 – Mean values (n = 3) of root mass share [%] of oil radish (violet), crimson clover (red) and winter rye (green) at different soil depth in 2018 (A, B) and 2019 (C, D) in a 50:50 cover crop mixture of oil radish and winter rye (A, C) and in a 33:33:33 cover crop mixture of oil radish, crimson clover and winter rye (B, D). Different uppercase letters indicate significant differences ($p < 0.05$, t-Test) between proportions of root mass of mixture partners within one soil depth layer (Kemper et al., 2020)

In Ukraine, according to Pisarenko et al. (2012), legumes (sainfoin, alfalfa, spring vetch, sweet clover, lupine, seradella) are mostly sown as green manure and green manure, which are more useful for enriching the soil with nutrients. Oil radish, mustard, buckwheat, phacelia, and others are widely used. Mixtures are also sown, such as spring vetch and spring oats, oil radish and spring oats, etc.

Under the influence of legume green manure, the number of nodule bacteria increases by 4–7 times, the enzymatic activity of the soil increases significantly, its phytosanitary and water-physical properties improve, and conditions are created for the intensive development of microorganisms and microfauna that determine the fertility of a given field. The positive effect of green manure lasts for 3–4 years.

The widespread introduction of green manure helps to incorporate unused reserves of phosphorus, potassium, calcium, magnesium and other plant nutrients from deeper soil genetic horizons into the small cycle.

Green manure crops are grown with a cover crop, in a row crop and a harvest crop. In the first case, in the year of cultivation, green manure is sown under a cover crop (spring barley, corn for green fodder, etc.) or sown directly after harvesting the main crop (stubble, harvest). In the process of growing green manure crops with a cover crop, the field is cultivated using the technology of soil preparation for the cover crop. For the purpose of growing green manure after mowing or harvesting, the soil is prepared with the recommended aggregates to a depth of 6–8 centimeters. The main thing is to prevent a gap between harvesting the predecessor and sowing the green manure, as this leads to significant moisture loss and, as a result, poorer development of the green manure crop. It is also important to ensure that the seeds are planted in moist soil. Sowing is carried out immediately after tillage or simultaneously with it. The main method of sowing is conventional row sowing; seeding rates for post-mowing or stubble sowing are increased by 20–25% compared to optimal conditions (when sowing in spring) and seed is planted 1–2 cm deeper. After sowing, rolling, pre-emergence and post-emergence harrowing with light sowing harrows is carried out, and inter-row cultivation is also carried out on wide-row crops. The best results for friendly germination and subsequent growth of green manure are obtained by surface tillage: moisture is retained, the negative effects of erosion are minimized, weeds are reduced and the number of passes of the machines is reduced, and the soil is not compacted. In combination with green manure, surface tillage provides the most effective way to preserve and improve soil fertility. Growing green manure crops improves the fertility of the soil created by the plants themselves. This property has even been calculated mathematically. During its lifetime, a plant takes only 10 percent of its «material» from the soil to form biomass, and 90 percent comes from the air and the energy of the sun's rays (Pisarenko et al., 2012).

Thus, for each ton of dry matter harvest (main and by-products), perennial legumes (alfalfa, sainfoin, clover) fix about 30–38 kg of nitrogen from the air, lupine and fodder beans – 20–27 kg, peas – 10–15 kg. Surface tillage and residues on the surface of plant residues significantly increase nitrogen fixation by legumes. The best results for friendly germination and subsequent growth of green manure are obtained by surface tillage: moisture is preserved, the negative effects of erosion are minimized, weeds and weeds are reduced, and the amount of At the same time, it is important to replenish the soil with basic nutrients, which improves the mineral nutrition of plants. The data obtained by the author are presented in Table 3.16 (Pisarenko et al., 2012).

Thus, increasing the specific mass of biological nitrogen and other nutrients in agroecosystems by increasing the area of green manure (primarily legume green manure crops) is the main lever for stabilizing the productivity, energy and economic efficiency of agriculture.

The author concludes that green manure is one of the main factors of the organic farming system. This measure is mandatory in transitional (rehabilitation) farming, as well as in intensive farming. Its use enriches the soil with organic matter, increases the amount of nutrients, and generally improves soil fertility and profitability. The use of green manure virtually eliminates the need for additional mineral fertilizers, which is an environmentally and economically sound measure.

All of this ensures an increase in production profitability, contributes to the ecological rehabilitation of the soil, improves its fertility based on biological principles of farming, and protects the environment. The widespread introduction of green manure contributes to the transition to a resource-saving and, in the future, organic farming system.

The choice of green manure is determined by the biological characteristics of the plant, including its relation to the level of soil fertility, taking into account the content of humus and nutrients, and the reaction of the soil solution is also important. Cereal crops such as winter rye and its varieties (green rye and perennial rye), oats, and ryegrass can tolerate high soil acidity and low nutrient content. Legumes, unlike cereals, grow better on fertile soils (except for perennial lupine), do not require additional nitrogen, but do not tolerate weeds and cannot grow significant biomass in a short growing season. Cabbage crops grow better on fertile soils, are suppressed by weeds, and react negatively to lack of moisture and nitrogen deficiency. They require a high level of farming culture, with the exception of oil radish, which differs from other cabbage crops in its need for soil conditions by its relative unpretentiousness. For post-harvest sowing, regardless of its purpose, only those crops are suitable that are primarily early maturing, insensitive to low air and soil temperatures and to a decrease in solar radiation and daylight hours, and cold and frost resistant. Plants from the cabbage family are such early maturing and heat-resistant crops, the best of which are spring and winter rape, white mustard, oil radish, winter and spring rape. Forms of green manure. The choice of green manure form is dictated by the soil, climatic and economic conditions of the agricultural producer. The form of green manure is determined by the choice of sowing or underplanting method of green manure crops.

Table 3.16

Agrochemical characterization of green manure plants by the calculation-equivalent method (Pisarenko et al., 2012)

Green manure	Green mass yield, c/ha	Accumulated nutrients in total biomass, kg/ha			Total, kg/ha	In stock, kg/ha 1*
		N	P_2O_5	K_2O		
Sainfoin	275	145	25	75	245	510.4
Winter vetch	250	160	75	200	435	906.3
Vetch-oat mixture	275	120	35	80	235	489.6
Fodder peas	350	80	70	90	240	500
White sweet clover	200	110	45	140	295	614.6
Annual lupine	520	230	60	200	490	1020.8
Buckwheat for two earnings	650	200	135	305	640	1333.3
White mustard	250	60	40	90	190	395.8
Ragweed	340	135	55	240	430	895.8
Oilseed radish	450	85	65	245	395	822.9
Phacelia	300	80	50	200	330	687.5

Advantages of green fertilizers (Advantages and disadvantages of green fertilizers, 2022):

1. *Nitrogen (N) accumulation*. Legume green manure enriches the soil with nitrogen, which is "taken" from the air by nodule bacteria located on their roots. The accumulated nitrogen is enough for both the green manure crop and the next one after it. With a green manure crop yield

of 350-400 c/ha, 150–250 kg/ha of total nitrogen is released into the soil, which is equal to the application of about 30-40 tons/ha of manure.

2. *Accumulation of humus*. Green manure is an important source of organic matter replenishment. Crops grown on green manure have different effects on humus accumulation. It depends on whether the ground mass of the green manure is used for fertilization, whether it is plowed into the soil at the place of growth with the root system, or whether only crop and root residues are plowed into the soil. The accumulation of humus also depends on the time of plowing the green manure. Spring plowing creates better conditions for the preservation and accumulation of organic matter. As pointed out by OM. Berdnikov points out, the green mass of a legume plowed in late autumn (150–200 kg) is equivalent to the application of 20 tons of manure per hectare, annual lupine gives 80–160 kg/ha of root and crop residues with a humification coefficient of 0.15–0.25, cruciferous plants, when used for green fertilization, leave 1.0–1.5 t/ha of plant residues or more than 200 kg/ha of humus in the soil (humification coefficient 0.15–0.20).

3. *Improvement of air and water regimes of the soil*. After plowing green mass of green manure along the passages of dead roots, aeration is good and the water regime improves.

4. *Less leaching of nutrients (N + Ca + K)*. On the sandy soils of Polissya, intermediate sowings of green manure during autumn rains delay the leaching of easily soluble forms of nutrients, especially nitrogen.

5. *More efficient use of nutrients from the lower soil layers for crop formation*. Rainwater in the upper layers of the soil dissolves nutrients and carries them to the lower horizons, but crops cannot use them from there. The roots of green manure absorb these nutrients from the groundwater and use them to form the mass, so the nutrients remain in the topsoil.

6. *Reducing erosion (soil consolidation)*. During the summer and autumn period, the soil under green manure is less eroded and less compacted by rain, water does not run off the surface, does not wash away its fertile layer, but is absorbed, replenishing moisture reserves. Therefore, green fertilizers should be considered as a measure to reduce water and wind erosion.

7. *Soil shading (soil protection)*. The soil under green manure does not overheat or dry out, and microorganisms and earthworms are active in it, which also work to enrich the topsoil with organic matter. The soil surface is

protected by the vegetation cover and, for a short period of time, conditions close to natural are created to restore soil fertility.

8. *Soil structuring (biological tillage).* K.I. Dovban found that the widespread introduction of green manure in Polissya crop rotations on sod-podzolic soil increases the content of not only the total number of water-resistant aggregates, but also its most valuable fraction – aggregates with a diameter of more than 1 mm.

9. *Loosening of arable and subsoil layers*. When growing green manure, the bulk of the plant roots are located in the arable and subsoil layers, which loosens the soil well.

10. *Reducing soil salinity*. Sweet clover is one of the salt-resistant crops, so it can be grown on saline soils as a phytomeliorant. After plowing sweet clover, salts from the saline horizons are washed out into the deeper soil layers through the passages of its dead roots. Its powerful root system also extracts calcium from deep soil layers, and after plowing and mineralization of the mass, it releases and displaces sodium from the soil-absorbing complex of the soil.

11. *Improving soil biological activity*. The use of green manure in crop rotations stimulates an increase in the number of soil microorganisms, enriches their quantitative composition and helps to increase the biological activity of the soil. As a result, soil fertility and crop yields improve.

12. *Weed control* by shading them with green manure and antagonistic action.

13. *Disease control*. When plowing the green mass of green fertilizer, the activity of a large group of saprophytic soil microorganisms, which are antagonists of many pathogens, increases.

14. *Pest control* (reducing the number of nematodes). When growing main crops, it is recommended to introduce green manure crops that repel nematodes into the crop rotation.

15. *Increase in the yield of the next crop with less nitrogen application* or greater efficiency of the impact of measures (fertilization, tillage). Widespread use of green manure helps to restore soil fertility and increase crop yields. The increase in yields from green manure is 1.7-4.3 cwt/ha for wheat, 50-90 cwt/ha for potatoes, 50-140 cwt/ha for sugar beet, 70-130 cwt/ha for corn, 9-13 cwt/ha for corn kernels, and 6-10 cwt/ha for buckwheat.

Disadvantages of green manure (Advantages and disadvantages of green fertilizers, 2022):

1. Some green manures have a narrow C:N ratio, which can lead to a decrease in soil organic matter. To prevent this, it is advisable to apply green fertilizer together with low rates of bedding manure (up to 10 t/ha) or with straw that remains on the field.

2. Lupine does not tolerate high soil calcium content, and therefore it is unprofitable to grow it on carbonate black soil. Therefore, other green manure should be used on these soils.

3. One of the disadvantages of green manure is the drying of the soil during the growing season. In dry periods, plowing them may be ineffective. This is often observed in green manure pairs when green manure is plowed late (shortly before sowing winter crops).

4. Loss of humus during very intensive cultivation in the warm season (for sowing winter intermediate or stubble crops).

5. High water consumption in arid areas with improper crop selection or high doses of nitrogen (possible absence or thinning of seedlings due to lack of water).

6. Widespread diseases (cereals, clover) or pests (nematodes) due to mistakes (wrong choice of crop or duration of its cultivation).

In agriculture, all technical and economic considerations and the accumulated experience of specialists culminate in the implemented crop rotation. Therefore, it is advisable to conduct experiments with green manure on every farm. However, the results obtained may vary greatly and should not be used on other farms.

The number of types of green manure crops that can be grown is very large. It is limited by the growing season of the crop, the type of soil (the possibility of cultivating it) and the climatic conditions of cultivation, especially the amount of precipitation, as well as the technical support of the farm and the cost of seed.

Green manure can be grown when:

– increasing the yield of the next crop;

– improving pre-sowing or main soil cultivation;

– reducing the amount of mineral nitrogen applied to the next crop;

– a large supply of available moisture in the soil due to the large depth of root penetration after green manure cultivation;

– reduction in the number of pathogens or pests when growing subsequent crops.

Green manure crops are an integral part of any farming system. Existing classical forms of green manure, due to climate change, are becoming ineffective due to the instability of precipitation at the time of sowing green manure crops, even in areas of sufficient moisture.

Depending on the type and purpose of growing crops, green manure can occupy the field for one or more growing seasons (independent crops), be grown together with another main crop or in its inter-rows (intercrops), as well as during a short period from harvesting one crop to sowing another (intermediate crops) or after the stubble of perennial grasses has grown back (fallow crops).

The green manure system must be identified with the crop production system, which is determined by soil and climatic conditions and the structure of sown areas.

In the green manure system, the initial determination of the possible volumes and methods of growing green manure crops is made taking into account the state of soil fertility, planned yields and the level of organic and mineral fertilizers. At the same time, green manure production is usually carried out without changing the existing structure of sown areas under the main food, fodder and industrial crops. An exception is allowed for green manure on completely degraded soils, during the reclamation of abandoned and new land development (Degodyuk et al., 2020):

There are 5 forms of green manure:

1. Independent and flocked form.
2. Under-sowing green manure, post-mowing.
3. Post-cutting (post-cutting).
4. Post-harvest.
5. Backstage form of green manure (annual or perennial and, in turn, mowing and non-mowing).

The main (independent) one consists in the use of perennial and annual grasses for green fertilizer and in the replacement of black manure with green manure. The fallow crops are sown in the fall or spring, using the entire green mass for fertilization, and, if necessary, the flocks. This form of green manure is possible for farms in any soil and climatic zone of Ukraine when growing annual and perennial grasses. It is promising for areas of unstable and insufficient moisture.

Sowing green manure – green manure seeds are sown along the rows immediately after sowing the cover crop. After the main crop is harvested, green manure mass is built up on a high cut, which is plowed under the next crop. Perennial lupine, seradella, and perennial legumes (clover, alfalfa, sainfoin) are sown under winter grain crops. The main types of fertilizers in organic farming are sown under the cover of winter crops in late autumn or winter on snow or in early spring with a seeding rate of 55–60 kg ha^{-1}. The effectiveness of lupine as a green manure increases when combined with winter crop straw. This form of green manure is suitable for all soil and climatic zones of Ukraine.

Intermediate green manure can be either post-mowing or post-harvest, depending on the timing of sowing. This is the most common method of green manure, especially when there is sufficient moisture and on irrigated land.

Post-cutting green manure is applied in the first half of the growing season after the field is cleared of annual grasses or corn for silage. With a longer growing season, post-mowing grasses accumulate more green mass, which is applied to winter cereals and spring row crops such as potatoes, corn, sugar beets and fodder. Crops such as oil radish, spring rape, and legumes such as lupine, sweet clover, and seradella are selected for this form of green manure. Part of the green mass of these crops can be used for livestock feed. This form of green manure, as well as the following post-harvest green manure, can be consistently guaranteed in areas of sufficient rainfall or on irrigated land.

Post-harvest green manure is carried out in the second half of the growing season after harvesting early grain crops – winter crops, barley; early vegetables – radishes, early cabbage, early cucumbers, etc. For this form of green manure, high-yielding crops with a short growing season are selected – mustard, oil radish, fodder cabbage, rapeseed, or mixtures of lupine, peas, vetch and oats.

The most effective application of green manure, according to the results of research by Ukrainian scientists, is observed in the cultivation of potatoes, fodder and sugar beets, corn, winter cereals, vegetables and fruit and berry crops (Nosenko, 2011).

According to Nosenko (2011), depending on the place in the crop rotation, an intermediate (insertion) form of green manure is most appropriate, which is divided into under-sowing (sowing under the main crop) and post-harvest and post-harvest (sowing after harvesting the main crop) forms. In this case, the green manure is plowed in during autumn plowing for the next year's harvest. The independent form of green manure should be used only in the form of green manure pairs for winter crops. For other crops, independent green manure is unprofitable, as the field remains unproductive for a year.

According to the method of green manure use, there are full use (the entire green manure mass is plowed), mowing (the aboveground mass of green manure grown outside the crop rotation is plowed), and flocking (combined). The latter is divided into two types: two mowings for green fodder and plowing of crop and root residues; the first mowing for green fodder and plowing of the flock of the second mowing (used as flock-siderata pairs under winter crops). Intermediate green manure is more profitable than the main one, so the timing of sowing is very important, as it determines the biomass yield and the reliability of green manure in general. Under production conditions, immediately after harvesting the main crop, surface tillage is carried out and green manure is sown. In dry conditions, pre- and post-sowing soil rolling is mandatory.

According to Likhochvor (2008), growing crops for green fertilizers is of great agronomic and economic importance. From the economic point of view, it is more expedient to grow them as intermediate crops, occupying the field with the main crop that will provide profit. They can be divided into three groups according to the length of the growing season:

– short growing season (45–60 days) – phacelia, white mustard, oil radish;

– medium growing season (60–80 days) – peas, narrow-leaved lupine, seradella, sunflower, etc;

– long growing season (more than 80 days) – yellow lupine, fodder beans, etc.

Two groups of crops are most suitable for green manure: legumes, which produce green mass rich in nutrients, especially nitrogen; cabbage, which is characterized by rapid growth and high yields of green mass.

When using cruciferous crops for green manure, it should be borne in mind that the biomass of oil radish, rapeseed, switchgrass and other crops is determined by the presence of nitrogen in the soil and the level of soil fertility. With low nitrogen reserves on poor soils, cruciferous green manure does not grow at all.

The Chernihiv Institute of Agricultural Research has identified the most suitable crops for green manure in the Polissya and Forest-Steppe zones in intermediate sowings: pre-sowing, post-mowing, and post-harvest forms (Table 3.17).

Table 3.17

Suitability of plants for green manure in intercrops (Nosenko, 2011)

Crops	Requirements for growing conditions	Seeding rate of seeds, kg ha^{-1}	Reproduction rate	Biomass accumulation (a/mass + roots), c ha^{-1}	Degree of suitability for green manure
Narrow-leaved lupine	Undemanding	200	15	240	XXX
Yellow lupine	Undemanding	200	4	200	X
Lupine perennial	Relatively demanding	60	10	200	XX
Red clover	Demanding	20	10	140	X
Seradella	Undemanding	50	12	180	XX
White sweet clover	Relatively demanding	20	30	150	XX
Peas	Demanding	300	5	120	X
Diaper pea	Demanding	250	6	120	X
Winter vetch	Demanding	60	7	160	X
Spring vetch	Demanding	150	10	110	X
Phacelia	Undemanding	15	20	120	X
Oat	Undemanding	180	11	80	X
Barley	Demanding	200	10	70	X
Winter rye	Undemanding	200	10	200	XX
Green rye	Undemanding	75	26	250	XXX
Perennial rye	Undemanding	100	20	250	XXX
White mustard	Demanding	20	50	100	XX
Winter rape	Demanding	15	67	130	XX
Percot	Demanding	15	53	150	XX
Oilseed radish	Relatively demanding	40	25	230	XXX
Annual ryegrass	Relatively demanding	40	15	210	XXX
Pasture ryegrass	Relatively demanding	30	16	180	XXX

Notes. The degree of suitability of the intermediate crop for green manure: XXX – high, XX – medium, X – weak, n – undemanding, c – demanding, r.d. – relatively demanding.

Possible options for growing green manure crops are presented in Tables 3.18–3.20.

Thanks to their well-developed root system, green manure improves the fertility of not only the topsoil but also the deeper subsoil and subsoil horizons: the nitrogen regime improves, the content of phosphorus and potassium available to plants increases, and positive changes in the physical and chemical state of the soil occur, while the fertilizing effect of manure is limited to the topsoil.

Table 3.18

Cultivation of crops for green manure in post-harvest crops (Shuvar, 1997)

Crops	Sowing period	Seeding rate of seeds, kg ha^{-1}
Spring vetch	July 1–31	120–140
Fodder peas (diaper peas)	July 1–31	180–230
Yellow lupine	July 1–31	170–200
Spring vetch + diaper + yellow lupine	July 1–31	40 + 120 + 60
Seradella	July 1–31	50–70
Yellow lupine + seradella	July 1–31	130 + 30
Spring vetch + yellow lupine	July 1–31	40 + 100
Fodder beans	July 1–31	250–300
Buckwheat	July 1–31	60–70
Sunflower	until August 10	30–40
Fodder beans + diaper + sunflower	until August 5	100 + 100 + 15
Phacelia	until August 15	8–10
Seradella + phacelia	until August 5	30 + 5
Winter vetch + phacelia	until August 5	40 + 6
Seradella + buckwheat	until August 5	40 + 40
Diaper + sunflower	until August 5	150 + 15
White mustard	until August 15	15–20
Oilseed radish	until August 15	15–25
White mustard + phacelia	until August 15	15 + 5

Peculiarities of growing crops for green manure in intercrops:

After harvesting the predecessor (mainly cereal spiked crops), the field is immediately disked in two tracks to prevent moisture evaporation from the soil, followed by leveling and rolling with any combined unit such as the Europak. It is advisable to leave tall stubble or straw chopped during harvesting on the field. When applying manure in crop rotation under organic and other fertilization systems, it is advisable to combine it with green manure cultivation, which will increase the aboveground and root mass of green manure by 2–3 times, reduce the loss of nutrients from manure by 2.0–2.5 times and, accordingly, increase the utilization rate of organic fertilizers by 1.6–1.8 times. The mass of intermediate green manure crops is incorporated into the soil with one pass of disks (October-November); with high and dense grass (yield over 35 t ha^{-1}) – with two passes. Pre-sowing tillage for the following early spring crops consists of harrowing (which levels the surface) and rolling. The soil surface remains lumpy after the autumn disk harrowing of green mass. Snow is well retained on it, which ensures the emergence of full sprouts 3-4 days after sowing. Green manure is a powerful factor in the interaction of biotic and abiotic processes that transform substances into forms assimilable by plants with the help of microflora. Green manure accumulates in the soil about the same amount of root residues as aboveground mass – 15–45 t ha^{-1}. The decomposition of organic matter in green manure occurs much faster in the soil than in fiber-rich crop residues.

Methods of green manure application according to Gospodarenko (2013):

The following methods of green manure application are distinguished: undercover, independent, intermediate (or insertion), mowing, felling, mowing and felling.

Undercover application. Sainfoin, lupine, clover, and sweet clover are sown as green manure.

It is self-sufficient. The crop occupies the entire field during the growing season or even for several years in a row (green manure or green manure). Under certain conditions, green manure should be used to replace pure fallow land, where the field remains unproductive for a year.

Intermediate or intercropping – a crop occupies the field between harvesting one crop and sowing another. Depending on the timing of sowing the green manure, it can be a subsowing crop (for example, lupine is sown under winter rye for green fodder in spring, and after mowing the rye, the green manure grows back and is then plowed) or a stubble crop (lupine is sown after harvesting spring or winter crops). This is the most common way to use green manure. The criterion for the possible use of green manure crops in stubble crops is the temperature at which vegetation stops. The most commonly used crops in this case are peas, vetch, white mustard, ryegrass, phacelia, rapeseed, and switchgrass.

Sowing of stubble crops is carried out immediately after harvesting the main crop. In these cases, the soil is not tilled, but direct sowing is used. A sufficient amount of green mass (10–20 t ha^{-1}) is usually accumulated before the temperature drops to +5 °C, which is plowed under.

Mowing green fertilizer. Green manure is grown on one field and used on another in the form of a mowed, chopped mass that is scattered across the field and plowed. Most often, perennial lupine is used for this purpose, which is grown in fallow wedges.

Mowing, or mowing and mowing, green fertilizer. The first mowing of green manure is used for livestock feed, and the growing crop is plowed into the soil.

The depth of plowing green manure affects crop yields and the humus condition of the soil. For example, shallow plowing of green manure significantly increases the yield but has little effect on the accumulation of humus in the soil; deep plowing, on the contrary. Deep plowing is especially important on light soils. After plowing peat or straw together with green manure, the decomposition of the former slows down, while adding manure or slurry, on the contrary, accelerates the decomposition of green manure.

It is especially important to know at what stage of growth and development the plants are plowed. Plowing them before legumes bloom or cereals spike activates microbiological processes in the soil, increases the yield of subsequent crops, but does not affect the quantity and quality of humus. This is because the delicate green mass of green manure is poor in lignin, mineralizes quickly and is not fixed into humus compounds.

It should be noted that plowing green manure in the early stages can provoke mineralization of soil organic matter and dry out the topsoil. Therefore, the green manure crop is chopped and covered before the soil freezes in the fall. In addition, it is possible to carry out backstage green manure for snow retention in winter with the mass of plants being incorporated in the spring with disk harrows and then plowed.

It is advisable to “destroy” weeded green manure crops with any continuous herbicide, taking into account the aftereffects on the next crop. In this case, the cost of green manure increases, and the mineralization of plant residues is slower.

In terms of their impact on crop yields, green manures are close to bedding manure in the amount of 20–30 t ha^{-1}, and the costs of their production and application are 2–4 times lower.

The use of green manure has positive effects, in particular, it prevents soil erosion and degradation; regulates soil and microbiological processes by stimulating the reproduction of microorganisms; improves soil structure and water properties; reduces plant disease; mobilizes soil nutrients; and reduces weed infestation.

Table 3.19

Fertilizer value of green manure crops (Novikov et al., 2013)

Crops	Applied to the soil (biomass, organic matter, c/ha, NPK, kg ha^{-1})									
	green manure				occupied field				recycling with manure	
	biomass	organic matter	NPK	N biological	root and crop residues	organic matter	NPK	N biological	organic matter	NPK
Lupine perennial	640	91	563	187	–	–	–	–	31	181
Narrow-leaved lupine	550	78	453	153	75	13	49	17	48	262
White sweet clover	540	119	655	176	165	49	160	43	44	247
Yellow sweet clover	506	109	617	163	152	46	148	39	24	141
Seradella	370	60	353	110	65	11	50	16	24	137
Fodder peas	450	59	343	97	45	8	27	8	27	234
Red clover	400	68	584	148	135	23	158	40	26	222
Pink clover	380	64	555	141	125	21	146	37	29	232
Oriental goat's fescue	450	72	580	160	110	19	113	31	22	107
Fodder beans	350	56	268	99	40	7	25	9	26	208
Horned lambsquarters	400	65	520	165	120	31	125	40	27	144
Spring vetch	330	53	359	109	33	6	29	6	26	162
Oilseed radish	450	65	404	–	45	7	32	–	23	134
Spring melilot	350	57	334	–	35	5	27	–	27	127
Spring rape	450	68	317	–	45	7	25	–	26	156
White mustad	410	66	391	–	40	6	30	–		

Table 3.20

Characteristics and fodder properties of green manure crops (Novikov et al., 2013)

Crops	Duration of vegetation *(period of mowing ripeness), days*	Number of mowings	Resistance to			Optimal soil pH	Harvest, c ha^{-1}		In 100 kg of green mass	
			frosts	droughts	waterlogging		green mass	seed	feed units	digestible protein, kg
1	2	3	4	5	6	7	8	9	10	11
Red clover	2–3/*50–70*	2–3	medium resistant	medium resistant	medium resistant	5–6	300–400	1.5–3.5	21.0	2.7
White clover	10/*55–60*	2	resilient	resilient	resilient	4.5–5.0	150–200	1.5–2.0	22.0	2.8
Horned bent grass	4–6/*50–60*	2–3	resilient	resilient	medium resistant	4.5–5.5	180–300	3–4	23.0	3.8
Blue-horned alfalfa	4–6/*50–60*	3–4	resilient	resilient	unstable	6–6.5	250–400	3–5	21.3	4.0
Goat grass	6–10/*40–50*	2	resilient	resilient	medium resistant	6–6.5	280–500	5–10	20.3	3.5
Sweet clover	*2/80–90*	2	resilient	resilient	resilient	5.5–6.0	300–500	5–10	18.2	3.4
Sainfoin	3–5/*55–70*	2	resilient	resilient	medium resistant	5.5–6.0	200–350	6–7	20.6	3.8
Timothy	*6–8/60–70*	2	resilient	medium resistant	resilient	4.5–5.5	250–500	4–8	28.8	1.7
Bindweed	8–10/*40–50*	2	medium resistant	medium resistant	unstable	5.5–6.0	200–500	1.5–3.5	20.3	3.2

(End of Table 3.20)

1	2	3	4	5	6	7	8	9	10	11
Awnless bromegrass	*12–14/50–60*	3–4	resilient	resilient	resilient	5.0–5.5	280–500	5–6	29.0	2.9
Tall ryegrass	*4–5/50–60*	2–3	unstable	medium resistant	unstable	5.5–6.0	150–300	2–4	18.4	1.8
Meadow fescue	*6–8/50–60*	2	resilient	resilient	resilient	5.0–6.0	150–250	2–3	27.5	3.0
Meadow bluegrass	15–20/*45–55*	1–2	resilient	medium resistant	medium resistant	5.5–6.0	100–150	1.7–4	24.5	3.2
Meadow foxtail	10–20/*50–60*	2	resilient	unstable	resilient	5.0–6.0	150–250	2–5	28.3	2.3
Festalolium	*3–5/50–60*	2–3	resilient	resilient	resilient	4.5–6.5	250–400	5–8	26.5	2.7
Winter rye	*2/55–60*	2	resilient	resilient	medium resistant	4.5–5.5	200–400	25–50	25.3	2.0
Lupine perennial	*4–6/80–90*	2–3	resilient	resilient	resilient	4.0–5.0	250–450	4–8	–	–
Annual lupine	1/*70–80*	1	medium resistant	medium resistant	medium resistant	4.5–5.5	200–500	10–30	19.7	3.5
Seradella	1/*75–85*	2	resilient	resilient	medium resistant	4.5–5.5	200–250	5–10	17.1	2.4
Spring vetch	1/*70–80*	1	resilient	medium resistant	medium resistant	5.5–6.0	150–250	8–15	20.0	3.8
Pea	1/*70–80*	1	resilient	medium resistant	medium resistant	5.5–6.0	150–300	10–30	19.2	3.1
Oilseed radish	1/*50–55*	1	resilient	medium resistant	medium resistant	5.0–6.0	300–600	6–10	14.6	1.9
White mustard	1/*55–60*	1	resilient	medium resistant	medium resistant	5.0–6.0	250–500	5–10	14.1	1.8

Post-harvest residues. Post-harvest plant residues (non-marketable part of the crop, stubble and roots) are an important input item in the balance of organic matter and the transformation of nutrients in the soil. Therefore, they can be considered a type of green manure.

The quantity and quality of post-harvest residues depends on the crop, variety and yield and varies within a fairly wide range, t/ha: perennial lupine – 2–3, clover – 3–7, alfalfa – 4–9, peas – 1.5–3, winter rye and wheat – 2.2–6.5, barley – 2–4.5, corn – 1.5–6, potatoes – 1–1.2, sugar beets – 1–1.5, rye for green fodder – 1–2, mustard – 0.4–1, perennial grasses – 5–11.

Intermediate crops of green manure can be used in three ways:

a) spring, when the green manure crop is sown and grown before the fertilized crop is sown;

b) autumn, when the green manure crop is sown and grown in the fall after the main crop is harvested until the onset of winter;

c) winter, when the green manure crop is sown before winter and uses the late autumn and early spring periods for its development.

Rapid climate dynamics towards warming significantly changes the conventional wisdom about the diversity of biological set and technological capabilities of some long-known crops. Previously well-known crops can show themselves under these conditions from previously unknown sides and demonstrate excellent productivity. It is advisable to test new crops that tolerate dry periods well, are undemanding to the soil, and are adapted to growing in deserts. These are plants from the legume family (woolly astragalus; naked, rough and Ural licorice; small, mouse and thin-leaved peas; tuberous and meadow chinu; Don and large sainfoin; large-flowered rue; false or common camel thorn), thin-leaved plants (Karelin reed, multi-stemmed and giant hairstalk, swollen sedge and colchicum) and many other crops. The main thing is that the land should not be empty, but covered with a green cover.

The roots of green manure loosen and structure the soil, improve its water and air regime. In this regard, cereal green manure plays a leading role. Cereal plants have a widely branched root system that divides the soil into small clods. This effect of green fertilizer is especially useful for heavy, compacted soils that are poorly penetrated by water and air. Therefore, in the crop rotation or crop rotation that should be used in the garden, it is very important to set aside a place for green manure so that the soil is exposed to the structuring and healing effects of green manure, approximately once every few years (Table 3.21).

Table 3.21

Features of different green manure and their soil requirements (Trofimenko, 2009)

Root system	Plant species	Removal of slumping substances from the soil*	Speed of develop-ment**	Desired soil type from – to	Desired pH from – to
1	2	3	4	5	6
Nitrogen fixers					
Deep, 150–200 cm	Lupine blue	+++	XX	Light to medium	Dougher acidic-neutral
	Lupine yellow	+++	X	Light	Acidic
	White lupine	+++	XX	Medium–heavy	Acidic–slightly alkaline
	Sweet clover	++	X	All kinds	Weakly acidic–alkaline
Medium, 80–150 cm	Fodder beans	+	X	Medium–heavy	Weakly acidic–alkaline
	Sowing vetch	++	X	Light–heavy	Weakly acidic–alkaline
	Sowing pea	+	X	Light–heavy	Weakly acidic–alkaline
	Seradella	+++	XX	Light	Very acidic–alkaline
Shallow, 0–80 cm	Mossy vetch	++	Wintering	All kinds	Very acidic–alkaline
	Field pea	++	X	All kinds	Very acidic–alkaline
	Incarnate clover	++	Wintering	All kinds	Very acidic–alkaline
	Hybrid clover	+	XX	All kinds	Very acidic–alkaline
Non-legumes					
Deep, 150–200 cm	Mustard	+	XXX	All kinds	Very acidic–alkaline
	Buck-wheat	+++	XXX	Poor	Acidic–neutral

(End of Table 3.21)

1	2	3	4	5	6
Medium, 80–150 cm	Rape	+	Wintering	Light–heavy	Acidic–neutral
	Melilot	+	Wintering	Light–heavy	Acidic–slightly alkaline
	Oilseed radish	+	XX	Light–heavy	Acidic–slightly alkaline
	Phacelia	++	XXX	Light–heavy	Acidic–alkaline

* Nutrient removal from the soil: + weak; ++ medium; +++ high.

** Development: slow X; fast XX; very fast XXX.

On light soils, the positive effect of green manure is to increase the water-holding capacity by enriching the soil with organic matter. On heavy soils, cereals and legumes with deep root systems, such as lupine, alfalfa, rye, barley, loosen deep layers of the soil, and this is important for facilitating water penetration into the soil and improving its water and air regime. Crops grown for green fertilizer do not produce any products in the year of cultivation, but improve soil health for 3–6 years.

It is necessary to keep in mind the sanitary gap between the predecessors of green manure plants and subsequent crops. For example, cabbage green manure should not be placed after other crops of this family, rapeseed, sugar beets and oil flax, which have common pests and diseases, as well as after sunflower. Legumes should not be included in crop rotations with peas and soybeans, perennial grasses with spiked and tilled crops (taking into account the effects of soil drying). However, grain-intensive crop rotations should be broken up with sweet clover or white mustard to combat root rot and improve biodiversity in the crop structure. Green manure is of great importance for the cultivation of newly developed areas. They help to restore the fertility of soils destroyed by construction and other works, where machines and people have completely destroyed or compacted the top layer. In addition, the roots of green manure plants secrete organic acids, which, interacting with soil minerals, convert phosphorus into a soluble state. Legumes and mustard are particularly active in this regard. In addition, some legumes and mustard absorb phosphorus from deep soil layers with their deeply penetrating roots. Phosphorus accumulates in the aboveground part of these plants and in their root system. After plant residues are embedded in the soil and decomposed, the topsoil is enriched with organic phosphorus compounds contained in them, which are transformed into a form accessible to plants by microorganisms. So the crop following this green fertilizer grows on soil enriched with available phosphorus.

The soil and climatic conditions in Ukraine allow a large number of crops to be sown with green manure (Table 3.22–3.23).

Table 3.22

Suitability of crops for green manure in intercrops (M. Shevchuk et al., 2012)

Crops	Requirements for growing conditions	Seeding rate, kg ha^{-1}	Reproduction rate	Green mass yield, c ha^{-1}	Suitability for green manure
Narrow-leaved lupine	U	200	5	240	XXX
Yellow lupine	U	200	4	200	X
Perennial lupine	R	60	10	200	XX
Meadow clover	D	20	10	140	X
Seradella	U	50	12	180	XX
White sweet clover	R	20	30	150	XX
Pea	D	300	6	120	X
Diaper peas	D	250	6	150	X
Winter rye	U	200	10	200	X
White mustard	D	20	50	100	XX
Winter rape	D	15	67	130	XX
Oilseed radish	D	25	50	250	XXX

Notes.

1. The degree of suitability of the crop for green manure. XXX – high, XX – medium, X – low. 2. Requirements of the crop to growing conditions: U – undemanding, R – relatively demanding, D – demanding.

At the same time, it is emphasized (Shuvar, 2014) that in the context of modern global climate change, which humanity has been experiencing in recent years, including in Ukraine, the task of protecting soil fertility, and with it, increasing the productivity and sustainability of agrophytocenoses, taking into account the soil and climatic characteristics of the zone, must be addressed in a comprehensive manner, within the framework of adaptive landscape energy and resource-saving farming systems, which, along with fertility restoration and soil erosion protection, ensure the preservation of agricultural landscapes and the environmental cleanliness of the human environment. The development and implementation of green manure farming systems is of great practical importance in modern agriculture in Ukraine. Being cheap, effective and widely available, green manure is an inexhaustible, constantly renewable source of organic matter in the soil.

It has been noted (Gospodarenko and Lysianskyi, 2018) that one of the main constraints to the widespread introduction of cover crops is the problem of soil moisture availability. The negative role of green fertilizers can be manifested by the fact that if intermediate crops use too much moisture, it may not be enough for the main crop, which negatively affects the yield of the latter. Therefore, it is recommended to use post-harvest green manure crops in regions with less than 600 mm of precipitation per year.

The most difficult conditions for green manure crops are when they are grown in the post-harvest period (July-August), which is characterized by the greatest moisture deficit in Ukraine. Its reserves in the 0–10 cm layer on the black soils of the Central Forest-Steppe are 3–8 mm. To prevent the complete evaporation of water from the soil intended for green manure, it is necessary to apply surface tillage, consisting of disking the soil by 5–6 cm, harrowing and rolling the surface with ring rollers, together with harvesting winter crops, and, as an exception, one day after harvesting.

Such cultivation, especially at night, destroys the capillaries between the upper cultivated and lower untreated layers with more moisture (from which water rises up through the capillaries). This stops its evaporation and helps to gradually moisturize the upper layer. Dew is especially important for young green manure plants in case of insufficient soil moisture, because it is the only thing that saves plants from dying in dry, hot weather, and falling from the plants, it improves the moisture content of the soil surface and the soil air.

Table 3.23

Characteristics of certain types of green manure plants (Shuvar, 2014)

Crops	Preferred soil type	Nitrogen storage	Vegetation period / sowing period
Blue alfalfa (*Medicago sativa*)	Except for acid and moisture	Yes	From one year
Hop alfalfa (*Medicago lupilina*)	Except for acidic	Yes	From 3 months
Horse beans (*Vicia faba*)	Heavy	Yes	Before the winter
Vetch, pea (*Vicia sativa*)	Except acidic and dry	Yes	2–3 months
Incarnate clover (*Trifolium incarnatum*)	Light	Yes	2–3 months, before winter
Meadow clover (*Trifolium pratense*)	Rich loams	Yes	3–18 months
Narrow-leaved lupine (*Lupinus angustifolius*)	Light acidic moist	Yes	2–4 months
White sweet clover (*Melilotus albus*)	Any, including poor	No	Before winter
Sandy sainfoin (*Onobrychis arenaria*)	Any, including poor	Yes	From the year
Horned loosestrife* (*Lotus corniculatus*)	All types	Yes	From the year
Seradella (*Ornythopus sativus*)	Any moist	Yes	2–4 months
Buckwheat (*Fagopyrum esculentum*)	Any, including poor	No	1–3 months
Tansy phacelia (*Phaceba tanacetjfoha*)	All types	No	1–3 months
Rye (*Secale cereale*)	All types	No	Before winter
White mustard (*Sinapis alba*)	Any, including poor	No	1–2 months
Oilseed radish (*Raphanus sativus*)	Heavy clay soils	No	2–3 months
Comfrey (*Symphytum*)	All types	No	From the year

The amount of water formed from dew overnight reaches 0.1–0.5 mm. And in a year, it falls up to 40 mm, which is the amount that corresponds to the monthly precipitation rate in the Central Forest-Steppe in April or

August-November. Dew is formed mostly on a flat but rough soil surface, which is the case with the technology of direct tillage for green manure. This technology helps to preserve the remaining water in the soil that was not used by the predecessor, promotes the accumulation of water in the surface layer of the soil due to its rise from the lower layers. This ensures that the plants germinate fully 3–4 days after sowing, and their dense grass stand is an environment for the formation of a large amount of dew, which saves the plants from death in the first days of the growing season. Even the smallest rains (3-5 mm), which are considered ineffective in agronomy, are very useful for post-harvest green manure. More abundant rains (up to 10 mm or more) moisten the soil first to a depth of 15 cm, and then to the full depth of the root layer. Such conditions, combined with warm weather in July-September, contribute to the intensive growth of green manure, prevent the reproduction of weeds and pests.

Research conducted at the Khmelnytsky State Agricultural Research Station made it possible to develop a way to reduce the impact of weather conditions on the productivity of crops in a five-field grain rotation by post-harvest sowing of white mustard for green fertilizer. In extremely dry periods of grain cultivation in this crop rotation, under the influence of green manure, the reserves of productive moisture in the upper layer (0–40 cm) of the soil were 15–25% higher.

Nitrogen in the green mass of plants plowed into the soil is contained mainly in the form of protein compounds. In the process of its mineralization, ammonification and nitrification occur first, and the nitrogen in green manure is converted into compounds available for plant nutrition.

The rate of decomposition of the earned sidereal mass depends on a number of conditions. The type and age of the siderate, the granulometric composition and soil moisture, and the depth of cultivation are important. The older the plant, the heavier the granulometric composition and the greater the depth of the fertilizer, the slower it decomposes.

It is indicated (Gospodarenko and Lysyanskyi, 2018) that in order to speed up decomposition and obtain nutrients in a form available to plants, the depth of siderate must be less. And vice versa, if the goal is to increase the content of humus in the soil, it is necessary to earn it more deeply, since the humification coefficient increases with slow decomposition. Deep plowing is especially important on soils of light granulometric composition. Slows down the decomposition of siderates of earning together with legumes relatively inert materials that decompose slowly (peat, straw). The same effect is obtained when mixing in sowing for sideration of leguminous and cereal crops. Adding manure or slurry, on the contrary, accelerates the decomposition of green manure.

In the first year of operation, the nitrogen utilization rate of green manure is usually higher than that of manure. In addition, leguminous siderates have a well-developed root system that penetrates deep into the soil, so they absorb nutrients from the lower layers of the soil, as well as phosphorus and other nutrients from poorly soluble compounds. In this regard, during the decomposition of the earned plant mass, the upper layer of the soil is enriched not only with organic substances and mobile nitrogen compounds, but also with phosphorus, potassium, calcium and other elements.

The phase of growth and development of plowed plants is of particular importance. Cultivation of side crops in the phase before flowering of legumes or earing of cereals activates microbiological processes in the soil, increases the yield of subsequent crops, but does not affect the quantity and quality of humus. This is explained by the fact that the tender green mass of siderate is poor in lignin, is quickly mineralized and is not fixed in humus compounds.

When the biomass yield of sideral culture is up to 150 t ha^{-1}, it is plowed into the soil, and when the yield is more than 150 t ha^{-1}, it is first rolled with rollers or crushed with disc harrows or mulchers, and only then plowed. Continuous action herbicides can also be used to stop the growth of siderates.

Additional grinding of plant biomass into green fertilizer increases the costs of their application, however, longitudinal grinding of siderable mass accelerates biochemical processes due to the increase in the surface area of these materials and the improvement of the contact of microorganisms with the substrate. In addition, crushed cider mass is more evenly moistened, supplied with oxygen, and therefore decomposes faster. It retains moisture well due to a violation of the capillary system and prevents heat loss through organic mass. As a result of the acceleration of the processes of destruction of organic substances due to grinding, their consumption for the vital activity of cellulose-destroying microorganisms increases.

Generalized long-term research by German scientists (Gospodarenko and Lysyanskyi, 2018) showed that in order to achieve a balance of humus in the soil without a deficit, depending on the crops grown in crop rotation, it is necessary to earn the following amount of green fertilizer: for the cultivation of grain crops – 38 t/ha of green mass, and row crops – 75–100 t ha^{-1}. In terms of the degree of influence on the yield of crops, siderates are close to litter manure at the rate of 20–30 t ha^{-1}, and the costs of their production and application are 2–4 times lower.

Each sideral culture has its own characteristics of use for fertilizer. Thus, it is advisable to chop the green mass of cabbage for winter grain crops, disk it and after 14 days to earn, leguminous crops – to chop and earn without prior exposure in the upper layer of the soil. These features are related to the chemical composition of sider crops and, first of all, the C:N ratio in the mass, which determines the rate of its mineralization and the availability of nutrients for fertilizing crops.

Positive from the point of view of the potential of green manure use of oilseed radish in comparison with other traditional crops is the depth of rooting of oil radish plants, which sometimes reaches the level of rooting of sunflower (AHDB Horticulture, 2020) (Figures 3.12–3.13).

Extensive research has systematized and classified a set of sideral crops according to the directions and terms of their possible application. This summary information according to a number of studies (Rosenfeld and Rayns, 2010, 2010a, b, 2012) is presented in Table 3.25.

For South America, the list of effective cover and green manure crops is as follows: black oats (Avena strigosa Schreb), rye (*Secale cereale* L.), triticale (Tritico-cereale), oilseed radish (*Raphanus sativus* var. *oleiferus* Metzg), white bitter lupins (*Lupinus albus* L.), blue bitter lupins (*Lupinus angus*tifolius L.) common vetch (*Vicia sativa* L.), hairy vetch (*Vicia villosa* Roth), forage peas (*Pisum sati*vum subspecies *arvense*), chick peas (*Lathyrus sativus* L.), serradela (*Ornitophus sativus* Brot.), sunflower (*Helinthus annuus* L.), rygrass (*Lollium multiflorum* L.) etc. The most commonly used summer cover crops are millets (*Penisetum americanum* L., *Sorghum bicolor* L etc), foxtail or German millet (*Setaria italica* L.), sunnhemp (*Crotalaria juncea* L.), lab-lab (*Dolichos lablab* L.), pigeon pea (*Cajanus cajan* L.).

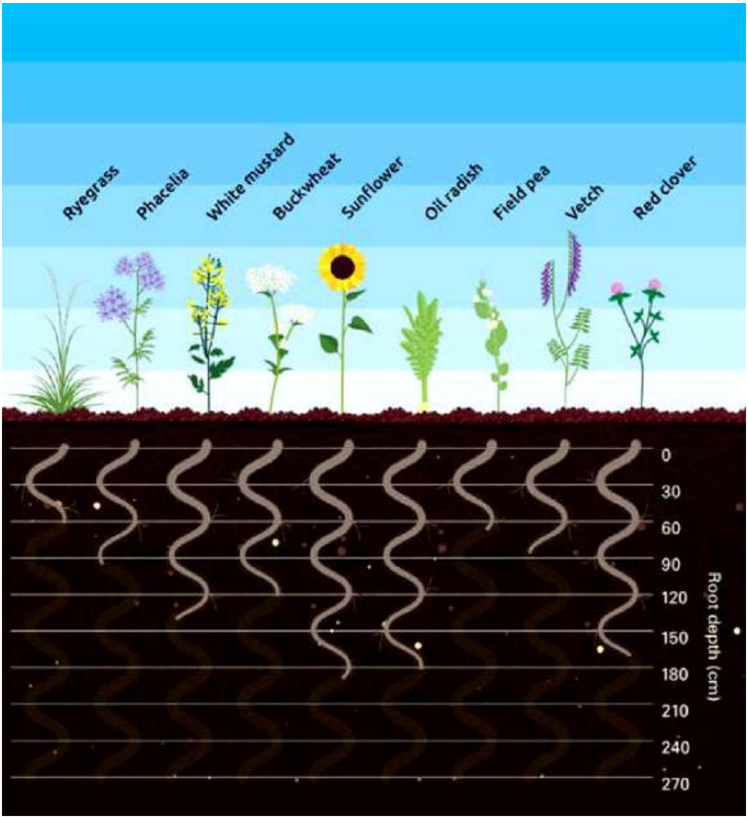


Figure 3.12 – Green manure species have different attributes, e.g. deep-rooted species can bring up nutrients, including trace elements, from the deep (AHDB Horticulture, 2020)

The following nomenclature and agrotechnological grouping is given for cruciferous plants of the Radish tribes in terms of their use in the green manure system (Radishes, 2021, 2022; Forage Radish, 2021; Forage Radishes, 2022):

Forage radishes (Raphanus sativus var. longipinnatus) are members of the Brassica family, which also includes arugula, mustard, and cabbage, to name just a few. Forage radishes are also known as Tillage radishes, Daikon radishes, and Japanese radishes. They are marketed under various cultivar names such as 'GroundHog', 'Nitro', 'Sodbuster', and 'Bio-till'.

Figure 3.13 – Process of root formation and rooting of oil radish plants

Oilseed radishes (*Raphanus sativus* var. *Oleiformis* Pers) are another type of radish grown as a cover crop. They are related to the forage radish but have a stubbier taproot, more branches, and tend to be somewhat more winter hardy than the forage radish. Oilseed radishes are marketed under cultivar names such as 'Adagio' and 'Colonel'. As the name implies, oilseed radishes were originally grown for oil. Often the names oilseed and forage ('Daikon') are used interchangeably, and that can be confusing because they are different. However, most of the traits and growing recommendations are the same for both types of radishes.

Forage radishes are excellent at breaking up compacted soils, and have earned the nickname "bio-drills." Planted in the early fall, 3 to 10 weeks before the first freeze, the roots of forage radishes can penetrate compacted soils more deeply than other cover crops such as cereal rye. Under ideal conditions, the thinner part of the taproot can grow to a depth of 6 feet or more during the fall! The thick fleshy part of the taproot can grow 12 to 20 inches (including 2 to 6 inches protruding above ground), creating vertical holes and zones of weakness that tend to break up surface soil compaction. After the plants die in the winter and the roots decompose, the open root channels can be used by the roots of your vegetable crops to grow through the compacted layers of soil. The channels created by the roots tend to remain open at the surface, improving water infiltration and soil warming in the spring. The channels also provide an access route for subsequent roots to reach subsoil moisture, resulting in greater plant resilience under drought conditions. The decomposed roots of the forage radishes improve the soil's porosity (air spaces) and the general physical soil condition (tilth).

Weed Suppression. A good stand of radishes – more than 5 plants per square foot – has been shown to eliminate nearly all winter annual weeds. Weed suppression from fall-planted radishes typically lasts into April but does not extend much further into the summer planting season.

Nutrient Scavenger. The deep root system, the rapid root growth, and the heavy feeding of forage radishes combine to make them an excellent scavenger of residual nitrogen after the summer growing season. Radishes take up nitrogen from both the topsoil and from deeper soil layers and then store the nitrogen in their shoots and in their root biomass. Because radishes do an excellent job of cleaning up nitrogen left over in the soil from summer crops, they help prevent nitrogen from leaching into groundwater during fall, winter, and spring.

Unlike cereal rye (annual winter rye), whose residues decompose slowly and continue to hang on to nitrogen for extended periods (thus immobilizing the nitrogen), radish roots decompose and release nitrogen rapidly. This means that early spring crops can get an early boost from the nitrogen captured by the radish crop.

In addition, forage radishes have also been shown to be excellent scavengers of potassium (K) and phosphorus (P) left over from the past growing season.

Effects on Nematodes. Research has provided evidence that the residues from radishes reduce the number of plant parasitic nematodes such as root knot nematodes.

Seeding. It is difficult for the home gardener to determine the ideal seeding rate, but several seed packets I reviewed suggested rates of ¾ lb. to 1 lb. per 1,000 square feet. Follow the seed company's recommendation listed on the seed packet and adjust the sow rate after a season or two of experience.

Table 3.25

Overview of the main green species and mixtures which have potential as short-term green manures in UK vegetable and salad production (Radishes, 2021, 2022; Forage Radish, 2021; Forage Radishes, 2022)

Species	Plant type	Annual/ perennial / biennial	Approximate ideal duration	N fixer	Speed of N release on cultivation	Good nutrient lifter	Best for soil structure improvement	Good for organic matter	Good for very short summer terms (<2 months)
Red clover	legume	perennial	1–4 years	√	fast	√	√	√	
Crimson clover	legume	annual	6–9 months	√	fast	√	√	√	
Persian clover	legume	annual	5–12 months	√	fast	√	√	√	√
Sweet clover	legume	biennial	6–18 months	√	fast	√	√		
Yellow trefoil	legume	annual	6–18 months	√	fast	√	√		
Vetch	legume	annual	6–10 months	√	fast				
Grazing rye	cereal	annual	6 months	X	slow	√		√	
Mustard	brass i ca	annual	2–4 months	X	slow			√	
Tillage (oilseed) radish	brassica	annual	3–6 months	X	slow	√	√	√	√
Buckwheat	polygo-naceae	annual	4–6 months	X	moderate				√
Phacelia	borage	annual	4-6 months	X	slow				
Chicory	composite	perennial	1–5 years	X	moderate		√	√	
Perennial ryegrass	grass	perennial	1–5 years	X	slow			√	
Cocksfoot	grass	perennial	2–5 years	X	slow			√	
Italian ryegrass	grass	perennial	1–2 years	X	slow			√	
Westerwolds	grass	annual	6–12 months	X	slow			√	
Red clover & ryegrass	mixture	perennial	1–3 years	√	slow			√	
Rye & vetch	mixture	perennial	6 months	√	slow	√			
Ryegrass & vetch	mixture	perennial	6 months	√	slow			√	
Mustard & mixed clovers	mixture	perennial	4–6 months	√	fast				
Oats, peas and vetch	mixture	annual	3–6 months	√	fast			√	
Yellow trefoil & white clover	mixture	perennial	6–18 months	√	fast				

The recommended depth for seed planting is ¼ to ½ inch, however, seed can be broadcast (remember my brother in-law's air plane method?) and left uncovered. The recommendation is to sow uncovered seeds about 50 per cent more thickly. So, if the recommendation is to sow 1 lb., sow about 1½ lbs. if the seeds will not be covered with soil.

Radishes germinate rapidly, emerging within 3-4 days when environmental conditions are favorable. Seed broadcasted on the soil's surface can establish well if followed by a timely rain. Forage radishes do not tolerate very wet soil, so low spots that collect standing water should be avoided. The radishes are tolerant of frost until temperatures dip below 25ºF. It takes several nights of temperatures in the low 20s to kill forage radishes.

Cautions. Deer will be attracted to your forage radish crop. Also, during warm spells in winter and in early spring, decomposing radishes may release a pungent rotten-egg odor.

Since forage radishes are in the Brassica family, it's best to avoid planting them in areas where you will be planting other Brassica members such as cabbage, cauliflower, broccoli, kale, kohlrabi, turnip, or mustard.

Another great tool in the cover-crop tool box, forage radishes can provide multiple benefits including: alleviation of soil compaction, weed suppression, nutrient capture (N, P &K), and erosion control. They can also be mixed with other cover crops such cereal rye to add more organic material to your soil.

An important aspect is the use of green manure crops in the system of modern approaches to surface tillage and various crop rotation systems in terms of the duration of their rotation.

Thus, in studies (Derpsch, 2020) it was noted that it is not possible to talk about green manure cover crops without talking about crop rotation. In a no-till system we can not talk about crop rotation without talking about cover crops. Maximum diversification of the system should always be a goal when applying no-tillage techniques. Mixtures of cover crops should be preferred over the use of a single species. Green manure cover crops are the cornerstone of sustainable agriculture and should always be included in sound crop rotations. Green manure's and cover crops are used as synonyms in this paper. In a no-till system cover crops are incorporated biologically and not by tillage implements.

Green manure cover crops should:

– be of low cost (seeds);

– be easy to seed and manage;

– provide good weed control and shading;

– produce a positive residual fertilizer effect on following cash crops;

– they should not compete in area, labor, time and space with cash crops.

Monoculture, that means the continuous seeding of the same crop, in the same place during many years has only been possible in the case of rice. This crop has been cultivated as the only crop sometimes for centuries in highly populated areas in Asia. In general monoculture results in diminishing productivity per unit area, the maintenance of low productivity's, or in extreme cases the complete loss of production. In general the following factors are responsible for this situation (Derpsch, 2020):

– Increase of specific diseases and pests.

– Increase of specific weeds.

– Reduced availability of nutrients due to changes in biological activity and physical degradation of the soil.

– Reduced root development.

Accumulation of specific toxic substances that inhibit growth. The principles and fundamentals of crop rotation are:

– To alternate plant species;

– with different rooting depth;

– with different ability to absorb nutrients that are susceptible to diseases with those that are resistant;

– taking into account positive & negative effects of one crop on the next;

– that tend to mine with those that tend to increase soil fertility;

– with different needs in terms of labor peaks, machines & implements, water, etc. (Derpsch, 2020).

In a no-till system the use of crop rotation is much more important than in conventional tillage systems. Experience has shown, that tillage negates cover crops. Also cover crops are essential for producing the mulch needed in the no-tillage system. Cover crops have to be integrated in the agricultural system of each farm and show their beneficial effects.

The main functions of green manure and cover crops are as follows:

Provide soil cover for:

– no -tillage;

– increasing water infiltration into the soil;

– reducing water evaporation;

– reducing soil temperature;

– protection against erosion reducing weed infestation;

– accumulation of organic matter in the soil;

– adding and recycling nutrients;

– improve soil structure;

– promotion of biological soil preparation.

Adding of organic matter in the soil is often mentioned in the literature as one of the main objectives of cover crops, but this can in general and (especially in warmer climates) only be achieved in the no-tillage system.

Benefits of Green Manure Cover Crops

Cover crops are a key element to make sustainable agriculture possible and have shown the following benefits in Latin America:

– Higher economic returns when appropriately chosen.

– Reduce the need for herbicides and pesticides.

– Improve yields of following cash crops.

– Conserve soil moisture (when properly managed).

– Prevent soil erosion.

– Enhance organic matter content of the soil.

– Provide nitrogen.

– Avoid leaching of nutrients and improve soil fertility.

– Reduce fertilizer costs.

Possibilities of Reducing Weeds and Herbicides Costs with the Use of Cover Crops in No-Tillage:

One of the most recent and fruitful lessons we have learned n the no-tillage system is that farmers should, if possible, never leave the land in fallow. In general fallow periods of only a few weeks will result in weed proliferation, seeding of weeds, reduction of soil cover, soil erosion as well as lixiviation (le aching) of nutrients. The old farmers rule is still true, «one years seeding means seven years weeding». If instead of leaving the land in fallow, farmers seed any crop immediately or as soon as possible after harvest of the previous crop, they will reduce weed proliferation, avoid that weeds produce viable seeds, increase soil cover and the biomass returned to the soil, increase organic matter content of the soil, avoid soil erosion as well as washing out of nutrients, and improve biological conditions of the soil.

Generalizations were also made regarding the use of oil radish in the system of multifunctional use as a universal cover crop. In particular, Chammoun (2009) noted that oilseed radish (Raphanus sativus) is a cover crop that has been used in sugar beet production to aid in soil pest control. (Hafez, 1998) Nematodes are plant pathogens that live in the soil and cause yield losses on a wide range of crops. In a study done by Saad Hafez of The University of Idaho's Cooperative Extension, an average level of 92% in nematode population reduction was observed when oilseed radish was used in rotation with sugar beets. (Hafez, 1998) Assuming oilseed radish could yield similar results on nematode populations in Georgia when used as a cover crop, a reduction of input costs could be achieved when economic crops were grown in the warm season. Six pounds of aldicarb per acre is the recommended rate of insecticide to apply on Georgia cotton when nematode populations are problem in the field. (Baird et al., 1995) Oilseed radish appears to have the potential to save this application of pesticide when used in a rotation with cotton in Georgia. Oilseed radish has also been observed providing additional benefits of soil compaction reduction, soil aeration, weed suppression, and nitrogen trapping. (Ngouajio and Mutch, 2004, Sundermeier, 2008) A reduction in soil nitrogen leaching during the cool season has also been observed. (Justes et al., 1999) With these benefits in mind, oilseed radish is commonly referred to as a green manure crop (Hafez et al., 1998).

In the study of Chammoun (2009) noted that the seed of the oilseed radish contains 40% oil by weight. (Eckey, 1954). A high oil value makes this crop a good candidate for biodiesel production also. Assuming a cover crop of oilseed radish could be grown and harvested as seed, leaving other crop residues in the field, could allow for added value in growing the crop in Georgia. In order to provide and estimate of the value of the co-products of oilseed radish we obtained assessments through personal communications from collaborators for three cases, cover crop, meal, and biodiesel. In the first case, viability as a Georgia cover crop was estimated by planting five plots totaling one acre were planted at the USDA National Peanut Research Laboratory in Dawson, GA in late September 2008 after peanut harvest.

Excellent germination was achieved and the crop has grown well with minimal inputs. Harvest is planned for May 2009 and yield data will be recorded (personal communication with Wilson Faircloth).

In the second case, value of the meal was estimated by crushing 200 pounds of seed, and the meal analyzed for its potential as poultry feed in Georgia. A feeding trial was done by Dr. Michael Azain of the University of Georgia's Department of Animal and Dairy Science (personal communication with Dr. Michael Azain). Results from the study confirm that oilseed radish has the potential to be used as a partial replacement in poultry feed in Georgia's poultry industry. More detailed and replicated studies will be needed to establish proper diets and levels of oilseed radish meal. Assuming the results from Dr. Azain's study will be replicated, a potential value for oilseed radish meal can be calculated based on the composition of the meal. To aid in the characterization of the meal, the following tests were reported: the fatty acid profile of oilseed radish meal, the plant tissue analysis, the proximate analysis, and the amino acid profile of oilseed radish meal (Table 3.26–3.27). The fatty acid profile provides a detailed description of the different carbon molecules that comprise the meal and oil. It is important to note the high level of erucic acid (22:1) similar to rapeseed. Also the fat content in the meal is typically higher than soybean meal (fat content of 1%) because this meal was extracted with only a screw type press, and not using solvents which would be typical in industrial uses. The proximate were found to vary from soybean meal. For comparison, soybean has 48¬49% crude protein, 3.9% crude fiber, and 1% fat. (Chammoun, 2009).

Previously made conclusions about oil radish are also confirmed by Frank (2015) who noted (with reference to other authors in the author's statement) that the practice of using cover crops in corn-soybean rotations is relatively new and becoming of great interest to many producers in the Corn Belt region of the United States. However, the concept of using plants to cover soil and recycle nutrients has been practiced historically by many. Farmers essentially replicated most natural ecosystems, realizing that having plants actively growing, covering the soil, transpiring water, taking up nutrients, fixing carbon, and supporting soil fauna benefited the environment (Kaspar and Singer, 2011). As a first priority, cover crops were traditionally used by farmers to cover bare soil and reduce erosion. Many cover crop species were also used for grazing livestock to save costs on additional feed sources, suppress pests, and provide nitrogen to a succeeding crop. Even with many traditional farmers using cover crops, farmers may not have completely understood the benefits and effectiveness of cover crops.

Table 3.26

Fatty Acid Profile of Oilseed Radish Meal (Chammoun, 2009)

Fatty Acid (n=3)	Percent (%)
16:0	6.13
16:1	0.05
18:0	1.68
18:1	23.87
18:2	13.46
18:3	10.34
20:0	0.68
20:1	8.58
22:0	1.64
22:1	31.76
24:0	0.61
24:1	1.26
Saturated	10.74
Monounsaturated	65.51
Polyunsaturated	23.75
Fat Content in Meal	18.48

Current research is now starting to show the true successes and efficiency of cover cropping, and therefore creating an interest amongst producers, conservation tillage, including no-tillage systems (Blevins et al., 1983). Researchers and producers have recognized that conservation tillage systems increase residues on the soil surface and reduce mechanical manipulation and mixing of soil (Blevins et al., 1983). Cover crops can be an effective means of increasing surface residues, and are often implemented when using conservation tillage practices. This is especially true in the Corn Belt, where cover crops are grown in the fallow period after cash crop harvest which lasts six to eight months out of a year (Kaspar and Singer, 2011). Based on their function within a given system, cover crops are also classified as «green manures,» «catch crops,» or «living mulch» (Kaspar and Singer, 2011). Magdoff and Van Es (2009) define each of these terms individually and further describe how the term «cover crop» is most widely used because farmers usually have multiple goals when planting these crops and many species fit into more than one of the classifications.

Table 3.27

Plant Tissue Analysis of Oilseed Radish Meal (Chammoun, 2009)

Element	Average Value (n=5)
Ca	0.33%
K	1.31%
Mg	0.46%
N	5.41%
P	1.27%
S	2.35%
Al	24.32 ppm
B	8.8 ppm
Cd	< 0.4 ppm
Cr	< 1 ppm
Cu	5.72 ppm
Fe	75.65 ppm
Mn	28.28 ppm
Mo	1.72 ppm
Na	44.28 ppm
Ni	< 2 ppm
Pb	< 5 ppm
Zn	44.52 ppm
Moisture	7.35 %
Crude Protein	35.04 %
Fat	17.97 %
Crude Fiber	5.42 %
Ash	6.28 %

Despite recent movements to protect their valuable water and soil resources, cover crops have had limited adoption in the Midwestern U.S. Singer (2008) reported that only 11% of Corn Belt farmers planted cover crops between 2001 and 2005, and therefore he concluded that farmer surveys were needed to understand how cover crops fit into farmer expectations and farming systems. Singer et. al. (2007) found that 18% of Corn Belt farmers have used or tried cover crops on their farms, primarily for reducing soil erosion and increasing soil organic matter. The authors determined that most farmers in the Corn Belt are aware of cover crop benefits, but educational programs focused on cost, selection and management need to be initiated to fill information gaps between the researcher and producer. Arbuckle et. al. (2014) took a distinctive approach when surveying farmers based on their belief that climate change is or is not occurring. Results indicated that 63% of farmers tend to believe that climate change is occurring and would likely respond by using adaptation and mitigation strategies against extreme weather events. Ultimately, cover crops could be used as one adaptation and mitigation strategy in conservation farming practices; however, effective communication between researchers and producers regarding cover crops needs further improvement.

Frank (2015) also noted that many state and governmental agencies have more recently developed subsidy programs for timely planting and management of cover crops. Weil and Kremen (2007) stated that despite the state of Maryland having paid subsidy programs, cover crop adoption has been low, with only 20–25% of cropland hectares being planted to cover crops. Weil and Kremen (2007) also suggest most farmers are either unaware of direct benefits offered by cover crops or simply cannot afford the cost and trouble of cover crop implementation, even though most desire to improve the environment and cropland. Through extensive research and collaboration, Weil and Kremen (2007) hypothesized that when farmers are able to see multiple benefits of specific cover crops, farmers will realize that cover crops are a profitable farming practice worth integrating into their production systems. For example, when using a five-state Corn Belt regional assessment model, Kladivko et. al. (2014a) found that if producers with acreage using corn-soybean rotational systems incorporated a cereal rye cover crop where suitable, the region as a whole could reduce nitrate leaching loss to the Mississippi River by approximately 20%. Ultimately, a main goal of most cover crop research today is to create a larger awareness of cover crops and the multiple benefits that can be generated through adaptation of cover cropping practices.

Recently, there has been much concern about cash crop growth under extreme weather events such as drought, large rainfall events, fewer rainfall events, floods, and severe heat stress. Variable climate presents uncertainty and challenges to managing soil and water resources in agricultural regions (Morton, 2014). Highly productive and intensely managed cropping systems such as corn and soybean in the Midwestern U.S. «often represent low diversity of land use and have a history of unintended consequences on soil and water quality» (Morton, 2014). As global issues such as increasing soil erosion, off-farm nutrient losses, and pollution of limited water supplies occur, on-farm adaptation strategies must occur to successfully address these issues (Morton, 2014). Cover crops could serve as a promising adaptation and mitigation strategy when it comes to increased climate variability. Using the upper Mississippi River Basin as a model, researchers found that implementing a rye cover crop reduced impact of N pollution, reduced erosion potential and nutrient losses, and would continue to be more effective if grown every winter fallow period as compared to production systems with tillage and no cover crop present (Panagopoulos et. al., 2014). Additionally, researchers concluded that the use of cover crops as a mitigation strategy would positively affect environmental and economic sustainability during future decades of adverse climatic conditions (Panagopoulos et. al., 2014). Therefore, implementing cover crops in the Midwestern Corn Belt region could potentially serve as a sustainability approach both economically and environmentally during periods of climatic variability and uncertainty.

More recently, along with a sparked interest in cover crops, many farmers in the Midwest have needed to address the issue of protecting and conserving our soil resources. As a result, many producers are shifting from conventional tillage.

Benefits of cover crops As mentioned previously, cover crops provide multiple potential benefits to soil and subsequent cash crops, while also improving the environment. Actual benefits of a cover crop depend on the species and productivity of the crop (Magdoff and Van Es, 2009) as well as its management, such as timing of planting and termination. Additionally, benefits from cover crops may require several growing seasons before benefits are noticeable (Kaspar and Singer, 2011). Therefore, it is important to research and quantify the benefits of cover crops to gain further insight on when and how benefits may occur.

Perhaps the greatest benefit of introducing a cover crop into rotations with a fallow period is implementation of a beneficial soil management practice (Kaspar and Singer, 2011). Cover crops enhance nutrient cycling through scavenging in fall and release in spring, protect topsoil from erosion and runoff, support soil microorganisms, increase organic matter, and suppress cash crop pests. Even though yield benefits may not be detectable right away, improvement of land, soil and water resources are possible as well as cash crop growth and yield improvements.

A fall brassica species such as oilseed radish (OSR) *(Raphanus sativus* L.) grow faster in the fall and accumulate more N in its large, fleshy taproot as compared to oats. Due to its deep-penetrating taproot, OSR can scavenge N from deeper soil layers that is quickly transported beyond the rooting zone of most plants, further aiding in decreasing N leaching losses and increasing N conservation (Dean and Weil, 2009). In addition, OSR is excellent at creating soil macropores and penetrating through compacted layers because of its large taproot (Horton, 2013). In addition to the large taproot, OSR can accumulate large amounts of leafy aboveground biomass which contributes to accumulation of soil N. The amount of N scavenged by OSR depends largely on amount of biomass growth, timing of fall establishment, residual N in the soil profile, and optimum environmental conditions for fall growth (Horton, 2013).

In Maryland, forage radish and OSR were more efficient than rape and rye cover crops at scavenging N during fall growth and further depleting the soil profile of NO3-N and contributing to soil N conservation in the fall (Dean and Weil, 2009). However, the researchers concluded that OSR may have been releasing NO_3-N too early for the succeeding corn crop based on large amounts of available spring soil NO3-N concentrations. Justes et. al. (1999) found less spring nitrate concentrations in drained water from fields grown with an OSR cover crop as compared to no cover crop; 45 and 91 mg NO_3- L^{-1}, respectively. When monitoring fodder radish, winter rye, and ryegrass ^{15}N uptake after a growing season of bare soil, only 18 kg N ha^{-1} was left under radish treatments, as compared to 59 and 87 kg N ha^{-1} under winter rye and ryegrass treatments, respectively (Kristensen and Thorup-Kristensen 2004). In addition to N cycling, OSR can also aid in providing surface soil P availability in the spring in the vicinity of radish root holes left behind after decomposition of residues (White and Weil 2011). The OSR may be able to survive several frosts before complete winter-kill occurs, more so than forage radish, making OSR a popular cover crop choice for simple management and great N scavenging capabilities (Clark 2007).

According to the results of research by Frank (2015), the following aspects of the efficiency of using oil radish as a covered and green manure crop were established:

– Results indicate that OSR bicultures have potential for rapid fall growth and N scavenging. There was reduced potential for fall N losses in all OSR treatments at DTC as compared to the no cover crop control treatment. Therefore, OSR-based cover crops have great potential to reduce soil-N losses (approximately 10 kg N ha^{-1}) in the fall by scavenging N and storing N in aboveground biomass tissues and can serve as a valuable conservation tool in Midwestern cropping systems to reduce N leaching and runoff losses.

– Rigorous soil sampling in the spring (March-June) allowed for multiple snapshots of soil-N concentrations throughout the period of cover crop residue decomposition and corn establishment. When OSR and oat residues started to decompose in early spring, N was released back into the soil profile and was highest in the uppermost layer of the soil profile (0–15 cm) throughout the duration of this study. In general, soil NO_3-N concentrations increased with time in the spring, and soil NH_4-N concentrations increased with time in early spring, and then decreased with time in late spring. Spring soil-N concentrations tended to be highest at position B (2.5 cm away from cover crop row) as compared to position C (7.6 cm away from cover crop drilled row). Due to cover crop decomposing in the spring, NH_4-N and NO_3-N concentrations were highest closest to decomposing surface residues.

– The OSR/rye treatment greatly reduced soil-N concentrations in spring and results suggested fairly little N leaching in this treatment due to rye actively growing in the beginning of spring during the first two sampling times and residues not decomposing until later in the season as compared to OSR and oat residues decomposing earlier. Therefore, it is important to realize N will most likely not be readily available at corn establishment from cereal rye. Rye needs to be terminated approximately two weeks before corn planting to initiate residue decomposition and to avoid a prolonged period of N tie-up in residues. These results show that OSR bicultures can have large impacts on soil N concentrations during the spring, with

OSR/oat providing additional N and OSR/rye providing less N as compared to the OSR alone treatment, in general. Cover crop treatment did not have an effect on soil PSNT concentrations in June of 2014.

– All OSR treatments most likely reduced the amount of N leaching during the fallow period as compared to the no cover crop control treatment. Without a cover crop, a considerable amount of N could have been lost in the off-season, prior to corn establishment in spring. However, decomposing cover crop residues did start releasing large amounts of N early in the spring, indicating the importance of timely corn planting in order to benefit from N released in spring following a winter-killed cover crop.

– Corn still received the recommended fertilizer rates following the OSR cover crop treatments as to not hinder corn growth and achieve reasonable yields. In order to fully understand N contributions from OSR cover crop systems, it would be optimal to perform an N-15 study to monitor N scavenged and released from cover crop residues and utilization of that N in corn plants starting at establishment in spring.

This experiment demonstrates that cover crops can be an effective way to protect the soil and scavenge excess nutrients during the fallow period, even with smaller amounts of growth and variability in fall temperatures. Sampling OSR root tissues to determine N content in those tissues would have had a positive impact on this research. Horton (2013) was able to sample OSR taproots and oat and rye fibrous roots and concluded that a significant amount of N was scavenged and stored in the belowground tissues. Further research is necessary to determine exactly when OSR and OSR biculture cover crop residues have peaks in N release throughout the spring. As mentioned previously, N-15 may be one valuable technique to monitor N cycling in cover crop systems. In addition, soil sampling should extend through the entire spring season and begin as early as possible in the spring. Soil sampling throughout the entire corn growing season would also help determine soil-N patterns. This study, as well as a study by Horton (2013) were one year studies. Therefore, multi-year studies would be beneficial to determine effectiveness of OSR and OSR bicultures at reducing N leaching and increasing inorganic-N concentrations during the spring for use of the following cash crop.

Similar conclusions, especially regarding the positive impact of oil radish on nitrogen biorecycling, were made in the study of Lövgren (2022), where it was noted potential in decreasing N_2O emissions from OSR, but the results need to be confirmed through further studies. More broadly, research is also needed to determine the economic and practical feasability. The results for treatments 2 and 4 were not as expected, but raised questions and impulses for further research, eg. the question of whether the cutting of biomass made more intense, thereby increasing N_2O emissions.

There are many processes that produce N_2O in soils, but the main N_2O producing process during winter in temperate climates can often be assumed to be denitrification. There are three main parameters that need to coincide for denitrification to occur, that is 1. Microbially available NO^{3-} 2. Microbially available C, and 3. Oxygen limited conditions. Cover crops contain both NO^{3-} and C, so when frost sensitive cover crops are left in the field over winter, and therefore die and wither during frost, they release NO^{3-} and C, which becomes available for microbes to decompose. This in itself doesn't create nitrous oxide, but, if conditions are also oxygen limited, which it often is during winter when the soils and plants freeze and thaw, repeatedly, conditions become favourable for denitrification, and nitrous oxide production. One of these frost sensitive species is oilseed radish (*Raphanus sativus* var. *oleiformis*) (OSR). It has been seen to emit high levels of N_2O winter emissions, emissions that are in many cases higher than those from other cover crop species. At the same time, it is a species with several valuble characteristics as a cover crop. Therefore, further research is needed on how the high N_2O emissions from OSR could be mitigated (Lövgren, 2022).

The aim of this thesis was to identify management methods for decreasing N_2O emissions from the frost sensitive cover crop OSR. This was done by performing a field trial with four different treatments of OSR, including control. If the crop biomass is removed before the first frost, a large part of the C and N needed for the denitrification is not present when the soil starts to freeze and thaw, which should decrease N_2O emissions. Therefore, two treatments of OSR were 1. Harvest by cutting the plant material at a height of 2–3 cm, which meant that root and stubble were left in the soil, and 2. Harvest by pulling the plants up with the roots, removing both aboveground biomass and coarse roots. If soil denitrification is nitrogen limited, adding a C rich material, with a high level of C in relation to N, could decrease the N_2O emissions. This is due to the fact that when microbes decompose C rich materials they scavenge the surrounding soil for N, which limits substrate availability for nitrification and denitrification (Lövgren, 2022).

The field experiment was performed at the SITES Lonnstorp research station. 13 gas measurements were carried out about once a week between the 20 December and 3 March in field plots of OSR. Finally, the samples from the gas measurements were analysed on a gas chromatograph, so that gas fluxes could be calculated from the change in N2O concentration over time. 774.3 g ha^{-1} was the highest cumlative emission and it came from untreated OSR. Emissions from the uprooted plots were significantly lower than all other plots. During the first half of the study period, emissions from uprooted and cut were significantly smaller than those from the immobilisation treatment and untreated oilseed radish. These were expected results, indicating that N_2O emissions in period 1 were mainly related to the decomposition of organic material. During the second half of the study period, there were no significant differences between any of the treatments. It was surprising that the immobilisation and untreated did not emit higher levels of N_2O since no biomass had been removed from these treatments. One possible explanation for this is that the biomass that was left in the immobilisation and control plots could have had an insulating effect, while the removal of biomass in the cut treatment led to more intense freezing and thawing, and therefore larger N_2O emissions from the small amount of biomass left. Since uprooted was the only treatment that was significantly lower than the other treatments over the whole study period, removing all of the OSR biomass seems to be a better solution than the cutting of aboveground biomass (Lövgren, 2022).

The immobilisation did not significantly lower nitrous oxide emissions compared to control. This could be a result of that wood chips were not incorporated into the soil, that not enough material was added or that the particles were too large. Another possible explanation is that the N_2O emissions might not even be of soil origin. High emissions peaks from immobilisation and untreated OSR were registred already in the beginning of the study period; a time when the plants were still pretty upright standing and no considerable amount of withered biomass was present at the soil surface. This could imply that emissions have possibly originated from the aerial parts of the plant (Lövgren, 2022).

3.3. The effectiveness of the use of oilseed radish green manure in different variants of the technology of growing agricultural crops

Modern trends in the development of adaptive technologies for growing the main agricultural crops are based on a number of basic directions that take into account both the features of innovative changes and the technological renewal of mechanization, and the main trends in the development of agricultural production aimed at ensuring the environmental friendliness of the products obtained, soil conservation while ensuring the appropriate levels of economic and energy efficiency. One of the ways to ensure sufficient levels of environmental friendliness of final products for the cultivation of any crop is an appropriate system of using agrochemicals of various nature – pesticides, mineral fertilizers, growth-stimulating substances, etc. The use of the specified components in agrotechnologies of different levels and their ratio determines the actual level of biologicalization of the technology of growing a certain agricultural crop. There are, to some extent, two main approaches to assessing the level of biologization of the technology precisely according to the criterion of the fertilization system. One of them is based on the use of the fertilizer greening index, which is defined as the ratio of the amount of applied mineral fertilizers in the active substance per 1 ton of applied organic fertilizers. The other is defined as the ratio of the share of dosed fertilizer for the corresponding nutrient element, which is absorbed from mineral fertilizers to the total share of dosed fertilizer, absorbed from the full set of application forms of all mineral and organic fertilizers. At the same time, it is emphasized that the most expedient option of fertilizer for the majority of rural areas.crops should have a combined, namely, organo-mineral fertilizer character as the closest to the natural processes of plant nutrition and aimed at ensuring the conditions of ecologically oriented (organic) agro-technological production. Unfortunately, it should be stated that the modern realities of providing classical organo-mineral fertilizer are problematic, since they provide for the presence of a correspondingly sufficient amount of classic organic fertilizers and, in particular, semi-rotted manure. However, the degree of provision of this type of organic fertilizer for most regions of Ukraine is included in the rate of application at the level of 0.27-0.52 t/ha, which is significantly lower than the determined agrochemical rate of organic fertilizers in the system of regenerative agriculture at the level of 8-12 t/ha of arable land.

These aspects lead to an intensive search for effective alternative substitutes for classic organic fertilizers. Among these substitutes in agricultural practice, a permanent niche is occupied by sidereal crops. Sideration is considered as the most potentially capable means to ensure the necessary share of introduced organic matter in the general fertilization system and ensures the appropriate level of biologization of this fertilizer. Among the many plants that are traditionally used as siderates in the conditions of the research region, mainly white mustard, lupine, and annual mixtures are used. Oily radish should be added to this list, which, according to recent studies, demonstrates the multi-purpose nature of its own use and is a potential alternative to other sidereal crops for the use of sideral-mineral fertilization systems of agricultural crops.These conclusions are confirmed by a system of numerous studies on the use of oil radish as a siderate, emphasizing its significance and agrotechnological value summarized by the author of this monograph (Tsitsyura and Tsitsyura, 2015) (Table 3.28).

Table 3.28

Characteristics of oil radish as a green manure crop in case of systematic use during crop rotation (according to the summary data of literature sources for 1960–2014 (generalized by Tsytsyura and Tsytsyura, 2015)

Indicators	Significance
1	2
Options for green manure	All are possible: main, post-cutting, post-harvest, intermediate, winter stubble, etc.
Competitiveness	Very high, in combined crops it occupies mainly the middle and upper tiers, especially with an increase in the individual feeding area
Accumulation of plant biomass, t ha^{-1}	25–50
Reaction to additional mineral fertilizer	Positive in a wide range, especially for nitrogen forms of fertilizers: increase from 20 to 180%, depending on the fertilizer dose
Decomposition rate of green manure biomass	Intensive for aboveground leaf mass and slow for root residues
Intensive for aboveground leaf mass and slow for root residues	0.35–0.70

(End of Table 3.28)

1	2
Acidity reduction by pH value, units.	0.1–0.3
Volume of carbon dioxide emissions from soil, %.	Increase by 18–60 %
Soil structure coefficient	Increase by 1.15-1.23 times
Topsoil density, g cm^{-3}	Reduced by 12–28%.
Total soil porosity, %	Increase by 10–30 %.
Capillary porosity of the soil, %	Decrease by 8–20 %
Number of water-resistant soil aggregates, %	Increases by 3–14% over a 3–5 year cycle of use
Availability of hardly soluble salts and hardly digestible salts of soil minerals	Increases by at least 10–15% over a three-year cycle of use
Microbiological activity of the soil	Increase by 1.25–1.60 times, positive mobilization of organic matter increases, decomposition of straw and other post-harvest residues is accelerated
Soil heat balance, ^0C	General optimization with reduced amplitude (night – day)
Reduction in the number of soil nematodes, cysts m^{-3} of soil	Overall reduction by 1.3–2.0 times
Reducing the total weed infestation of the field, pcs. m^{-2}	Overall reduction from 30 to 95%.
Reduction in the number of wheatgrass, pcs. m^{-2}	Overall reduction from 40 to 78%
Type of field weediness	Changes towards the predominance of weeds of the late spring annual group
Accumulation of amino acids and active biological chemicals in soils	Increased content of sulfur-containing amino acids, increased concentration of brassinoteroids, inhibitors, antioxidants, a number of allopathic substances, etc.
Soil redox potential balance	Normalization towards a slightly acidic – neutral reaction
The rate of onset of physical maturity of the soil	Acceleration by 1 to 3 days depending on soil type
Macronutrient balance, kg ha^{-1}	Increase in balance sheet positivity by 15–40%
Nitrate accumulation in the soil, mg kg^{-1}	Reduction by 35–70% with regular green manure in crop rotation

(End of Table 3.28)

1	2
Nitrate accumulation in groundwater, mg l^{-1}	Reduction by 10 times with regular green manure in crop rotation
Accumulation of radioactive isotopes (Cesium-137) during greening of radioactively contaminated areas	A reduced isotope transfer coefficient from the soil is characteristic even on sandy and sandy loam soils
Increase in yields of spring and winter cereals, c ha^{-1}	Overall increase in the range of 15–60%.
Increase in sugar beet yield, c ha^{-1}	Overall increase in the range of 8–25%.
Increase in potato yield, c ha^{-1}	Overall increase in the range of 20–45 %
Increase in hop yields, c ha^{-1}	Overall increase in the range of 20–35 %
Phytopathological situation of the field	General improvement with a decrease of 1 – 3 points in the overall phytopathological assessment)
Costs of green manure	Relatively low in comparison with other green manure crops
The optimal soil and climate zone for green manure	Zones of sufficient and unstable moisture are optimal, with early or late autumn sowing dates, as well as southern and even arid zones. Ground cover – the widest range of options
The cost price as green manure	Lower than other crops from the cruciferous family by 22–35%.
Availability of soil moisture for the decomposition of green manure	Mandatory requirement of at least 55–70% field moisture content

The analyzed bibliography notes that oil radish is particularly effective as a green manure on poor and heavy soils: it improves the physical properties of the soil, reduces the risk of disease (reduces the number of soil pests and pathogens, such as root rot pathogens and nematodes, by 1.5–2 times), increases the yield of subsequent crops, and improves the overall health of the soil.

The intensity of decomposition of oil radish green manure has its own characteristics. Its plant mass mostly consists of leaves, which have a higher nitrogen content and a narrower carbon-to-nitrogen ratio, so that the aboveground mass decomposes faster in the soil and is the first priority soil nutrition for the next crop, while the roots, on the contrary, are thickened and decay last, rhythmically and gradually providing the soil and plant with nutrients. In addition, the green mass, when incorporated into the soil, deoxidizes it, acting similarly to lime, as it has an alkaline reaction of cell sap (Figure 3.14).

Sometimes oil radish plants are called “biological plows” because they have a powerful taproot system that penetrates deep into the subsoil (Figures 3.14–3.16). This is very important in the current trends of zero and minimal tillage. Due to its root secretions, it promotes the absorption of hard-to-reach phosphorus, potassium, calcium, and sulfur compounds from the soil-absorbing complex, which are utilized by the next crop in the crop rotation. The diameter of its root collar is 2–2.5 cm (about 1 cm for mustard), which allows it to penetrate much deeper than mustard roots, even on soils with heavy mechanical composition. The degree of drainage of the soil by radish plants increases, excess moisture goes to the lower horizons of the soil, and therefore in spring it reaches physical ripeness faster, which facilitates sowing at the optimal time. Radish performs especially well in a mixture with legumes that can fix atmospheric nitrogen, so in a mixture with spring vetch, this grass mixture accumulates up to 200 kilograms of biological nitrogen per 1 hectare.

Accounting for the amount of plant residues and the yield of aboveground mass of oil radish showed that their share in fertilized variants in spring crops is 30.4%, in post-mowing – 41.1%, and in post-harvest – 47.6% of the total biomass. The highest coefficient of root system productivity in oil radish is observed in spring crops 4.4–4.6. In post-mowing and post-harvest crops, it decreased significantly and amounted to 2.6–3.0 and 1.8–2.0, respectively (Moiseev and Mishurov, 1976). The coefficient of productivity of oil radish roots in spring crops can reach a value of 5.66, and in summer 1.3–1.9. It is also important that oil radish roots are a valuable component of biological fertilizer due to their chemical composition. In post-harvest oil radish crops, the ratio of plant residues to yield was 1.31–1.81:1.0 (Table 3.29). Due to this ratio, oil radish is an effective component of the positive biological cycle of nutrients during the rotation period of crop rotation) (Tables 3.30–3.31).

Thus, the amount of organic matter that enters the soil with root and post-harvest residues of oil radish depends on the timing of sowing, seeding rates, doses of mineral fertilizers and meteorological conditions. The largest amount of root plant residues is formed in intermediate crops of oilseed radish.

Table 3.29

Biomass accumulation (dry matter) by a number of intercrops, t ha^{-1} (average for an 8-year rotation) (Nikonchik and Vostrova, 1980)

Crops	All biomass	Biomass harvested from the field	Plant residues			Ratio of post-harvest residues to crop
			stubble	roots	in total	
Winter rye for green mass	62.3	35.0	8.6	18.7	27.3	0.78 : 1
Oilseed radish (post-harvest)	42.1	18.3	8.3	15.5	23.8	1.81 : 1
White mustard (post-harvest)	40.3	19.5	6.9	13.9	20.8	1.07 : 1
Winter rape (post-harvest)	39.9	16.0	8.5	15.4	23.9	1.49 : 1
Seradella (under-sowing)	25.0	12.4	4.4	8.2	12.6	1.02 : 1
Perennial fodder lupine (under-sowing)	25.4	8.9	3.4	13.1	16.5	1.85 : 1
Perennial bitter lupine (for green manure)	48.2	–	25.3	23.4	48.7	1.92 : 1

Table 3.30

Comparative chemical composition of the root system of a number of crops in the Northern region (Nosenko, 2011)

Crops	Chemical composition of roots, % on absolutely dry matter			
	N	P_2O_5	K_2O	Ca
Spring vetch	1.92	0.62	1.48	0.97
Oilsed radish	1.65	0.76	2.15	1.54
Silage mallow	1.28	0.30	2.35	0.92
Spring rape	1.52	1.00	2.08	0.36
Fodder beans	1.81	0.35	1.06	0.92
Sunflower for milling	1.15	0.27	2.97	0.72

It was also found (Pysarenko et al., 2013) that its green mass contains the same amount of nutrients as cow manure: nitrogen – 0.5%; phosphorus – 0.25%; potassium – 0.6%. The mass of plant residues grown on an area of 100 m^2 contains the following amount of mineral fertilizers (in terms of chemical composition): mineral fertilizers (in terms of chemical composition) 3–5 kg of ammonium nitrate; 2.5–3.5 kg of superphosphate;

3.5–5.0 kg of potassium salt. In the Forest-Steppe zone, plants of oil radish sowing accumulate on average 65–85 kg ha^{-1} of nitrogen, 24–30 kg ha^{-1} of phosphorus and 87–100 kg ha^{-1} of potassium, which confirms the high ability of this crop to accumulate the main mineral compounds and their further use by the main field crops (Table 3.32). According to M. Nowakowski (1996), with oil radish yields above 400 c ha^{-1}, N 75–120 P 40–50 K 210–240 remain in the soil, and with a yield of 462 c ha^{-1}, N86 P66 K248 accumulate in the soil.

Figure 3.14 – Harvesting of oil radish as a green manure in the budding phase for sowing buckwheat on the experimental field of VNAU (top position – the state of the field after disking with John Deere 637 disk harrows, bottom position – the state of oil radish plant residues on the 5th day after harvesting in the layer of cultivated soil) (Tsytsiura and Tsytsiura, 2015)

Figure 3.15 – Harvest residues of oil radish harvested as green manure after cultivation of the green manure plot on day 35 (emphasizing the value of oil radish as an effective green manure for rapid immobilization of macro- and microelements of green manure mass and slow root decomposition. In the lower photo, the undecomposed remains of the root system and the lower part of the stems of oil radish are clearly visible) (Tsytsiura and Tsytsiura, 2015)

According to Drinch (2011), due to the bulky mass of roots and low carbon to nitrogen ratio, the leaf mass of oil radish decomposes quickly and the nutrients contained in it are easily available for subsequent crops (Table 3.33). Based on the data presented in the table and taking into account the rate of availability of nutrients for subsequent crops at 10%, they will be absorbed at least 68 kg of nitrogen, 14 kg of phosphorus and 119 kg/t of potassium.

Figure 3.16 – Root system of oil radish at different seeding rates (top position) and white mustard at different seeding rates (bottom position) (Tsytsiura and Tsytsiura, 2015)

Antonets et al. (2010) indicates that at yields of oil radish leaf mass over 40 t ha^{-1}, N75–90 P20–30 K50–70 remain in the soil. According to Pysarenko et al. (2013), oil radish used as a green manure at high yields provides up to 395 kg ha^{-1} of NPK (Table 78), according to Dovban (2009), N30–45 P10–15 K30–50 per 10 t of leaf mass (Table 3.34), and at average productivity, even on poor soils, oil radish is able to accumulate, in general, 220–270 kg ha^{-1} of nitrogen (Tables 3.35–3.38).

Table 3.31

Amount of nutrients involved in the biological cycle by intermediate crops (for an 8-year crop rotation), kg ha^{-1}

Crops	Total used			Including						The ratio of nutrients left in the soil with plant residues to their removal with the harvest, %.		
				taken out with the harvest			returns to the soil with plant residues					
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Winter rye for green mass	110.0	30.30	113.0	77.40	19.60	90.30	32.40	10.70	23.10	41.90	54.60	25.60
Oilseed radish	92.80	37.40	113.0	59.30	22.90	70.10	33.50	14.50	43.30	56.50	63.30	61.80
White mustard	89.50	27.40	98.90	64.00	18.10	64.50	25.50	9.26	34.40	39.80	51.20	53.30
Winter rape	88.10	30.20	92.20	48.30	15.50	50.60	39.80	14.70	41.40	82.40	94.80	82.20
Seradella	60.30	17.80	40.70	40.40	12.00	29.90	21.30	5.80	10.80	53.00	48.30	36.10
Perennial fodder lupine	65.90	13.30	33.10	28.20	6.05	17.70	32.90	6.81	13.30	117.00	112.00	75.10
Perennial bitter lupine	144.0	29.00	66.60	–	–	–	144.00	29.00	66.60	–	–	–

Table 3.32

Amount of macronutrients in the aboveground mass of green manure crops at average yield levels of leaf and stem mass (in the flowering phase – beginning of fruiting), kg ha^{-1} (Pysarenko et al., 2013)

Green manure	N	P_2O_5	K_2O	CaO
Oilseed radish (all biomass)	69.08	29.87	93.35	33.61
Oilseed radish (post-harvest residues)	64.49	27.89	87.15	30.37
Spring rape (all biomass)	58.21	19.85	64.83	19.85
Spring rape (post-harvest residues)	56.63	19.31	63.06	19.31
Small mallow (all biomass)	160.39	36.22	168.16	124.18
Small mallow (post-harvest residues)	157.29	35.52	164.91	121.78

Table 3.33

Nutrient content in dry matter of oil radish (Drinch, 2011)

Nutrients	Concentration, %		Amount of nutrients, kg ha^{-1}		
	plants	roots	plants	roots	total
Nitrogen	3.8	2.5	371	305	676
Phosphorus	0.7	0.6	68	73	141
Potassium	5.8	5.1	566	622	1188

Table 3.34

Agrochemical characteristics of green manure plants (calculated by the equivalent method) (Pysarenko et al., 2013)

Green Manure	Green mass yield, c ha^{-1}	Accumulation of post-harvest residues in the total biomass, kg ha^{-1}			Total, kg ha^{-1}
		N	P_2O_5	K_2O	
Sainfoin	275	145	25	75	245
Winter vetch	250	160	75	200	435
Vetch-oat mixture	275	120	35	80	235
Fodder pea	350	80	70	90	240
White sweet clover	200	110	45	140	295
Annual lupine	520	230	60	200	490
Buckwheat for two earnings	650	200	135	305	640
White mustard	250	60	40	90	190
Barbaréa vulgáris	340	135	55	240	430
Oilseed radish	450	85	65	245	395
Phacelia	300	80	50	200	330

Table 3.35

Macronutrient content in the leaf and stem mass of different green manure crops and litter-based manure (Dovban, 2009)

Green manure, manure	In % of raw weight			Kg in 10 tons		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Manure	0.44 – 0.60	0.25 – 0.30	0.50 – 0.70	44 – 60	25 – 30	50 – 70
Lupine perennial	0.46 – 0.50	0.08 – 0.095	0.25 – 0.34	40 – 50	8 – 9.5	25 – 34
Narrow-leaved lupine	0.40 – 0.42	0.10 – 0.12	0.20 – 0.25	40 – 42	10 – 12	20 – 25
White sweet clover	0.60 – 0.70	0.05 – 0.08	0.18 – 0.23	60 – 70	5 – 8	18 – 23
Winter rye	0.30 – 0.35	0.10 – 0.12	0.25 – 0.30	30 – 35	10 – 12	25 – 30
Annual ryegrass	0.35 – 0.40	0.11 – 0.13	0.25 – 0.30	35 – 40	11 – 13	25 – 30
Seradella	0.40 – 0.50	0.10 – 0.15	0.30 – 0.40	40 – 50	10 – 15	30 – 40
Diaper	0.45 – 0.50	0.12 – 0.15	0.40 – 0.45	45 – 50	12 – 15	40 – 45
Cruciferous (rapeseed, rape, oil radish)	0.30 – 0.45	0.10 – 0.15	0.30 – 0.50	30 – 45	10 – 15	30 – 50
Phacelia	0.32 – 0.40	0.10 – 0.13	0.40 – 0.48	32 – 40	10 – 13	40 – 48

Table 3.36

Comparison of a number of fodder crops by nitrogen accumulation on sod-podzolic soils, kg/ha (Dovban, 2009)

Crops	Nitrogen content		Total nitrogen content	Ratio C:N
	nitrogen content	in post-harvest and root residues		
White sweet clover	150–200	50–70	200–270	12–15:1
Meadow clover	140–180	40–80	180–260	11–13:1
Oriental goat's milkweed	200–250	80–100	280–350	12–15:1
White mustard	100–120	60–70	160–190	11–13:1
Oilseed radish	150–180	70–90	220–270	11–12:1

A positive factor that emphasizes the importance of oil radish as a green manure is the high ash content of oil radish leaf mass. Thus, Melnychuk and Stelmakh (1996) reported that the highest accumulation of ash elements in the leaf mass of oil radish during summer sowing was observed in the phase of early flowering, and then decreased to 20–22% in the phase of pod formation. According to this indicator, oil radish is ahead of all green manure crops: fodder lupine and meadow clover by

2.6 times, white sweet clover by 2.14 times, spring rape by 2.0 times, white mustard by 1.86 times, and a mixture of spring rape and vetch by 1.5 times (Figure 3.18).

Table 3.37

Amount of organic matter and mineral nutrients entering the soil during plowing of post-harvest green manure (Feshchun, 2011)

Crops	Leaf and stem weight, t/ha	Dry matter		Content in dry matter							
				$N - NO_3$		Phosphorus		Potassium		Calcium	
		mass, %	t ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}
Beans	20.71	19.0	3.94	2.82	107.7	0.37	14.13	1.40	53.48	1.12	42.78
Lupine	19.50	19.2	3.74	3.14	117.4	0.36	13.50	1.53	57.22	1.15	43.01
Peas	18.22	20.4	3.72	2.65	98.6	0.36	13.4	1.36	50.59	1.16	43.15
Oilseed radish	20.62	18.3	3.77	2.56	96.5	0.64	24.1	1.25	47.13	0.96	36.19
White mustard	18.97	18.9	3.59	2.41	85.5	0.62	22.3	1.27	45.59	1.04	37.34
Beans + lupine + peas	20.28	19.7	4.00	2.87	114.8	0.37	14.8	1.44	57.60	1.14	45.60
Radish + mustard	20.51	18.7	3.84	2.44	93.7	0.63	24.2	1.27	48.80	1.00	38.40
Manure (control)	30.00	22.0	6.60	2.25	148.5	0.34	22.4	1.60	105.6	1.10	72.60

Table 3.38

Nutrient content in green manure biomass (Feshchun, 2011)

Crops	In % of dry matter		
	N	P_2O_5	K_2O
Sweet clover	1.95	0.33	1.07
Sainfoin	1.81	0.34	0.95
Winter vetch	1.86	0.31	0.93
Oilseed radish	1.49	0.24	0.81
White mustard	1.55	0.25	0.78
Rape	1.55	0.27	0.82
Vetch + oats	1.27	1.23	0.75

Figure 3.17 – Root system of oilseed radish variety Zhuravka at the flowering stage (Excavation was carried out to a depth of 20 cm to the level of sharp narrowing of the main root. It is noticeable that the bulk of the roots is concentrated in a soil layer 25-30 cm thin. The diametric branching of the roots (lateral lateral roots of different orders) ranges from 5–8 to 12–15 cm. The taproot penetrates the soil to a depth of 50-80 cm and is a thin cylindrical structure up to 1.5–3.5 mm thick, depending on the technological parameters of the formation of the stem with small lateral roots. The diameter of the root thickening in our studies ranged from 0.5 cm to 5.5 cm. We have noticed that there is a certain relationship between the diameter of the root thickening and the length of the root system in the main direction of its growth) (Tsytsiura and Tsytsiura, 2015)

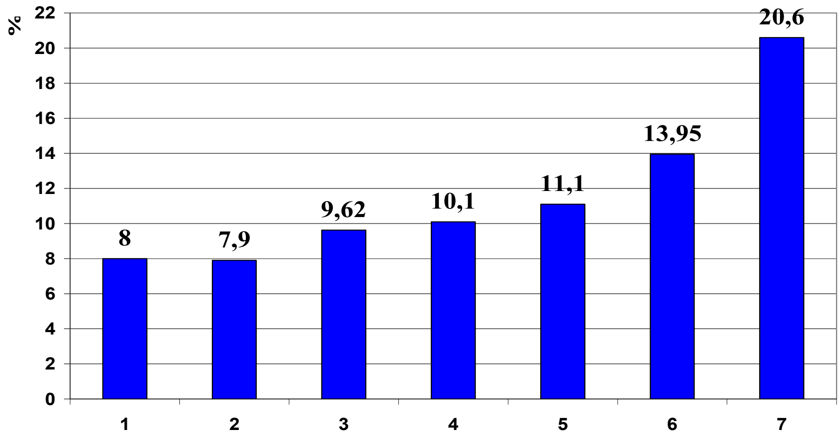


Figure 3.18 – Content of ash elements in the leaf and stem mass of green manure crops (full flowering stage): 1 – fodder lupine; 2 – meadow clover; 3 – white sweet clover; 4 – spring rape; 5 – white mustard; 6 – spring rape + vetch; 7 – oilseed radish (Melnychuk and Stelmakh, 1996)

It is also noted that even with summer and late summer sowing dates, oil radish under conditions of moderate moisture during the period of germination – pod formation is able to form at least 12–18 t ha^{-1} of leaf-stem mass, and under conditions of moisture of the period of full germination – pod formation at the level of 100–120 mm, even with these sowing dates, it is able to form up to 35 t ha^{-1} of leaf mass and 5.33 t ha^{-1} of dry matter at the beginning of pod formation, which can be successfully used for green manure or for other economic purposes starting from the budding phase (and even earlier). At the same time, the moisture content of the leaf-stem mass will be quite high, up to 95% (Table 3.39).

Dovban (2009) notes that the use of oil radish as a green manure not only has a positive effect on the accumulation of organic matter in the soil, ensuring a positive balance of macro and microelements, but also helps to improve the water and physical properties of soils. Thus, the use of oil radish for green manure reduced the density of the topsoil by 22% and the total porosity by 15% compared to the control. Under these conditions, capillary porosity decreased and non-capillary porosity increased. The decrease in soil volume was at least 15-18%. The author also notes that one of the disadvantages of green manure is the drying of the soil during the green manure growing season, and plowing it under other crops during dry periods reduces the efficiency of green manure. This is often observed in green manure pairs when, for some reason, green manure is plowed late, shortly before sowing winter crops. To avoid this, oil radish green manure in pairs should be plowed, depending on meteorological conditions, no later than 25–30 days before sowing the main crop. It is better to plow green manure for spring crops in late fall or spring. During the autumn-winter and early spring periods, soil moisture is restored to the optimum level for germination and development of spring crops. Observance of such conditions contributes to moisture conservation in the variants of green manure use – soil moisture in the layer of 0–40 cm was 6–12% higher than in the variant without green manure radish.

Table 3.39

Biological yield of oilseed radish by stages of organogenesis (Melnychuk and Stelmakh, 1996)

Stages of organogenesis	Moisture content of the leaf-stem mass, %	Dry weight, %	Yield, t ha^{-1}		Note
			leaf-stem mass	dry mass	
The budding of the flower	94.68	5.32	28.2	1.50	
The beginning of flowering	88.40	11.60	31.0	3.60	
Full flowering	86.30	13.70	34.6	4.74	Partial lodging
Pod formation	84.80	15.20	35.1	5.33	Full lodging

Kovalev V. P. et al. (1990) noted that the systematic use of oil radish as a green manure improves the overall soil structure. Thus, in the green manure plots, the number of water-resistant soil aggregates (0.25–0.50 mm) increased by 3–5% over 2–3 years, and the total clay content of the soil decreased by 2.5–6% in the first year of its use to 18–22% and 16–24%, respectively, in the 3rd–4th year of systematic green manure application.

The value of oil radish as a green manure is also in the fact that it grows rapidly, develops a large amount of leaf and root mass in a short period of 25 to 40 days, which opens up the possibility of its use in arid growing conditions and, in particular, at very early sowing dates.

For example, in recent years, the Central Experimental Farm of the Sumy Institute of Plant Industry has widely used oil radish as a post-harvest green manure for sugar beet cultivation. With the introduction of moderate doses of nitrogen, oilseed radish increased the amount of organic matter contained in 30–35 tons of manure in two months on one hectare. The use of green manure in combination with chopped straw made it possible to plow an amount of organic matter per 1 ha for sugar beet equivalent to the use of 45–50 tons of cattle bedding manure. In this case, the sugar beet yield was not inferior to the application of 40 t/ha of manure. The costs of all operations related to fertilization were reduced by 50–55% compared to the use of manure (Nosenko, 2011).

It has also been proven that post-harvest sowing of oil radish helps to reduce soil pollution with nitrate forms of nitrogen. The concentration of soil nitrates after oil radish was on average 70% lower than when sowing crops without using oil radish as a cover crop and as an intermediate green manure.

Oil radish also has a positive effect on the microbiological activity of the soil and improves the agrophysical and agrochemical properties of the soil and has a positive effect on the growth, development and productivity of subsequent crops in the rotation.

It is known that anthropogenic impact on agrophytocenosis significantly affects the structure of soil microbiocenosis and the total number of bacteria. In the studies of Rakhmetov (2000, 2012), the microbiological features of the soil rhizosphere were studied using different cruciferous green manure crops in comparison with the introduction of unhumified organic matter (Table). In general, the root secretions of oil radish were slightly inferior to mallow and contributed to the improvement of the rhizosphere zone, as indicated by the data on the colonization of parts of the soil by nitrogen bacteria. Compared to the control, when growing oil radish as a green manure, the phytotoxicity of the soil decreased by 1.5-2.0 times. Thus, the cultivation of oil radish is an important environmental lever for the formation of positive microbial communities in the soil rhizosphere.

Oil radish can be effectively used as an intermediate crop in short rotation crop rotations to improve the predecessor as an intermediate crop between the two main crops. In the conditions of agricultural production, especially taking into account the market orientation of specialization of many farms, it is not always possible to concentrate the main crops on the optimal predecessors. For these reasons, cruciferous intermediate crops, having intensive growth rates with the accumulation of high levels of biomass, allopathic properties due to the high content of sulfur-containing compounds, mustard oils, glucosinolates, indole substances and other physiologically active compounds, are an important reserve for optimizing crop rotations, reducing the negative impact of adjacent crops in the crop rotation through intermediate cultivation of the latter.

Under the influence of these substances, the virulence of some pathogenic bacteria in the soil is reduced. Root secretions of cruciferous plants reduce the germination of spores of pathogens and inhibit the length of their growth tubes.

At the same time, the content of microspore cells is also compressed, which leads to their destruction and death. Sowing of cruciferous plants also restrains the development of weeds, as their root secretions inhibit the germination of seeds of some weed species (Rakhmetov, 2012). Due to the rapid development of oil radish, the density of creeping wheatgrass weeds decreases. Scientists explain the death of creeping wheatgrass by the allopathic effect of cruciferous crops, which adversely affect the physiological and biochemical processes of acceptor plants, leading to inhibition of their growth and development and, as a result, death.

Allelopathically active substances enter the soil with root secretions during the life of the plant, as well as with crop residues of field crops, on which certain microflora settle. Gradually, the natural ratio between certain types of microorganisms shifts: the number of some decreases sharply, while others increase. In this regard, biologically active compounds are not involved in the cycle of substances and accumulate in the soil, having a harmful effect on certain crops. It is known that different green manure crops have different effects on the integrity of soil "breathing." Soil "breathing" is considered an indicator of its biological activity, the end result of which is the release of CO2, which is carried out by the entire soil biota and is an important indicator of the intensity of organic matter decomposition.

The intensity of carbon dioxide emission is an indicator of the rate of destruction of organic material. Determining the intensity of "breathing" of soils of different types when assessing agrotechnical measures establishes a link between this indicator and the biological potential of the soil.

Table 3.40

Microbiological activity of the soil rhizosphere under the use of cruciferous crops as green manure (Rakhmetov, 2000, 2012)

Variant	Spore bacteria on Mishustin medium, thousand/g abs. dry soil			CA nonspore bacteria, mln/g of abs. dry soil		
	timeframe for sampling (month)					
	May	June	July	May	June	July
No fertilizer (control)	94.2	81.8	11.6	3.6	2.5	2.9
Winter block						
Manure 20 t ha^{-1} (control)	130.4	51.0	90.4	8.3	4.0	5.7
Winter rape (total biomass)	82.4	99.1	129.2	10.1	3.3	1.6
Typhon (all biomass)	105.4	102.0	107.4	11.4	3.5	4.6
Spring block						
Manure 20 t ha^{-1} (control)	84.9	83.3	96.1	4.9	3.1	6.3
Oilseed radish (all biomass)	74.3	82.0	97.1	17.2	4.5	9.7
Barbaréa vulgáris (all biomass)	67.0	59.6	77.4	12.7	3.0	2.3
Small mallow (all biomass)	112.6	78.8	88.9	9.5	3.4	3.5
Variant	**Number of streptomycetes on cabbage agar. thousand /g abs. dry soil**			**Development of nitrogen bacteria. %**		
	May	**June**	**July**	**May**	**June**	**July**
No fertilizer (control)	254.6	943.2	138.7	48	78	38
Winter block						
Manure 20 t ha^{-1} (control)	294.0	1528.8	424.9	86	98	72
Winter rape (total biomass)	400.7	1288.0	184.6	98	90	77
Typhon (all biomass)	58.6	800.4	185.2	92	98	83
Spring block						
Manure 20 t ha^{-1} (control)	358.8	973.6	365.1	96	90	40
Oilseed radish (all biomass)	406.7	713.4	567.3	82	96	77
Barbaréa vulgáris (all biomass)	289.5	759.8	323.0	98	96	49
Small mallow (all biomass)	1138.1	1253.7	417.9	90	100	99

Oil radish is a fairly powerful emitter of CO_2 in the process of its decomposition in the soil after harvesting. Research conducted by Trofymenko and Bilan (2014) showed that different green manure crops are decisive in the value of CO_2 concentration with a directly proportional character depending on exposure. The studied green manure crops in terms of soil respiration (mg m^{-2} min^{-1}) in the same studies can be ranked in the following order: oil radish 73.7 – field diaper 42.0 – multiflorous ryegrass 39.2 – narrow-leaved lupine 35.6. Thus, the highest intensity of soil respiration is observed under oil radish. In the course of research by Trofymenko and Bilan (2014), it was also found that there is a high and medium degree of dependence between the yield of leaf-stem mass of green manure in the flowering phase and the intensity of soil respiration according to the correlation coefficient (r): oil radish and diaper 0.62, fenugreek 0.46 (medium degree), lupine 0.93 (very high degree).

Oil radish leaf mass can be successfully used to prepare multicomponent straw-based composts. The goal is achieved by adding to the straw, as a stimulant of the intensity of microbiological processes, easily hydrolyzable organic matter in the form of green mass of green manure crops in a certain amount (wet weight) per 1 ton of straw.

The green manure is applied to straw moistened with a solution of mineral salts – ammonium nitrate, superphosphate and potassium chloride, which are commonly used as NPK fertilizer. The amount of moisture in relation to the weight of the straw is 1:4 to 1:5. The concentration of mineral additives per 100 kg of straw is 2.8 kg of ammonium nitrate (1 kg of nitrogen active ingredient); 5.0 kg of superphosphate (1.09 kg of P_2O_5); 4.0 kg of potassium chloride (2.4 kg of K_2O). One of the recipes for this composting involves the use of enamel buckets with a capacity of 10 liters. The straw is chopped into 3 to 5 cm pieces, moistened with NPK solution at the above concentration, and mixed with the green mass of the green manure. It has been proven that the decomposition of such compost in the soil leads to an active reproduction of microorganisms. Thus, the content of bacteria in the soil (thousand grams of soil) was 6400 without green manure, 25000 with lupine, 24600 with rape, 19800 with oil radish, and 20300 with clover. Siderates are added in the amount of 0.2–0.3 dry weight, which corresponds to 80–120 kg of raw weight per 1 ton of straw. Composting is carried out without stirring at room temperature of 18–20 ^{o}C.

The results of using the proposed method of activating the straw composting process are presented in Tables 3.41–3.43.

Table 3.41

Influence of oil radish green manure on microbial growth in composted straw after 7 months, million g

Composting option	Types of microorganisms					General bio-geneticity
	cellulose-degrading	oil-sour	pectin-degrading	actino-mycetes	mushrooms	
NPK	5,88	79	12	11	2,5	563
NPK + green manure oilseed radish	15.88	277	22	66	7.6	3734

Table 3.42

Influence of oil radish green manure on mineralization processes during straw composting (after 7 months)

Composting option	Weight reduction, %					Ratio C: N
	total	cellulose	hemic-ellulose	pectin substances	lignin	
NPK	44.9	52.7	31.7	70.2	20.4	60
NPK + green manure oilseed radish	64.1	70.2	65.9	91.5	23.5	22

The obtained results confirm that the enrichment of straw with plant material that is easily hydrolyzed by microorganisms significantly stimulates the reproduction of all major physiological groups of microorganisms, as a result of which the processes of mineralization of hardly hydrolyzable components that make up straw are activated, which in turn contains on average (%): lignin 18 – 22; cellulose 33 – 35; hemicellulose 21 – 22; protein 3 – 5; mineral nitrogen 4 – 6. Compared to straw, green manure is enriched with water-soluble and easily hydrolyzable fractions of carbon-containing substances used by microorganisms as a source of food and energy.

The positive effect of oil radish on the microbiological activity of the soil and the nature of physical and chemical reactions was confirmed in the research of Rakhmetov (2012). He found that the introduction of green manure crops, including oil radish, affects redox processes in the soil by intensifying them (Table 3.43). This indicates an increase in the level of mobile substances released during the decomposition of plant mass.

The results of biochemical studies showed that the decomposition of green manure released organic substances that were in the soil in a free state, which is why their content is higher when using green manure. It should be noted that oil radish is one of the most active components of the studied green manure system in this regard, both in terms of free phenolic substances (for oil radish their concentration was 55 – 67 mg/kg, and in the control – 49–60 mg kg^{-1}), and especially in terms of the concentration of free amino acids in the soil (Table 3.44), which is evidence of its positive role in increasing the biological activity of the soil.

Table 3.43

Influence of green manure crops on redox potentials in soil depending on the developmental stages of spring barley, tV (average for two years) (Rakhmetov, 2012)

Variant	Bushing	Stemming	Before harvesting
Control – without fertilizers and green manure	262	265	331
Winter block (plowing in spring)			
Manure (20 tons ha^{-1})	301	280	250
Winter rocket-cress (all biomass)	276	285	322
Typhon (all biomass)	285	292	316
Spring block (plowing in the fall)			
Manure (20 tons ha^{-1})	268	272	279
Oilseed radish (all biomass)	275	272	307
Mallow (all biomass)	271	260	309
Spring rocket-cress (all biomass)	275	267	291

It is also noted (Rakhmetov, 2009) that plowing green mass of cruciferous and other intermediate crops also has a healing effect on the soil. In this case, the number of actinomycetes, which are antagonists of root rot pathogens, increases in the soil.

After harvesting the green mass, along with crop residues, plant growth and development stimulants from the brassinosteroid class remain in the soil, increasing yields and improving the quality of the marketable products of subsequent crops. All of the above suggests that growing cruciferous crops in intercrops will help reduce the use of chemical plant protection products in agriculture.

Table 3.44

The effect of green manure on the qualitative composition of free amino acids in the soil in the second decade of May, mg/kg (average of three years) (Rakhmetov, 2012)

Variant	Cystine	Lysine	Histidine	Aspartic acid	Glycine	Glutamic acid	Valine	Isoleucine	Leucine	Total
Control – without fertilizers and green manure	0.88	1.13	4.37	10.46	4.65	0.53	0.99	1.21	1.19	25.41
Winter block (plowing in spring)										
Manure (20 tons ha^{-1})	0.81	1.64	4.71	11.28	5.57	0.64	1.72	1.21	1.29	28.47
Winter rocket-cress (all biomass)	0.81	2.65	6.58	12.82	6.49	0.61	1.29	0.68	1.27	32.71
Typhon (all biomass)	0.84	1.30	5.75	12.92	6.43	0.86	2.01	0.61	1.21	31.93
Spring block (plowing in the fall)										
Manure (20 tons ha^{-1})	0.93	2.90	6.92	15.95	6.12	1.07	1.77	0.78	1.55	38.09
Oilseed radish (all biomass)	1.45	2.71	6.27	20.00	6.60	2.06	1.51	1.27	1.14	43.01
Mallow (all biomass)	1.84	2.41	6.30	18.75	6.24	0.83	1.87	0.72	0.74	39.70
Spring rocket-cress (all biomass)	0.96	1.69	5.02	11.61	5.04	1.69	1.24	0.78	0.64	28.67

Many studies have also emphasized the positive effect of oil radish as a green manure on the water and physical properties of the soil. Rubin (1985) found that the use of cruciferous green manure in the general block of spring green manure under different systems of garden row spacing contributed, on average, to an increase of more than 20% in the number of water-resistant aggregates (> 0.25 mm) (Table 3.45).

Zubets (2004) found that the use of cruciferous green manure has a multifaceted and complex effect on the change of agrophysical, agrochemical and biological parameters of different soil types and, in particular, leached chernozem in the Volga region: Increase in the amount of valuable water-resistant aggregates from 0.8 to 8.3% (2.0 to 3.2% for oil radish in particular); improvement of the soil profile structure within 1 to 3 years after green manure, reduction of soil density by 0.05 to 0.08 g/cm^3 (0.06 for oil radish); reduction of nutrient migration to deeper horizons from arable soil; restoration of the normal cycle of organic matter and nitrogen in the soil, etc.

Table 3.45

Effect of different soil containment systems on the amount of water-resistant aggregates > 0.25 mm, % (Rubin, 1985)

Soil retention option	Soil layer, cm	Average for the research period	
		absolute value	in relation to control
Black field	0 – 20	42.5	100
	20 – 40	55.7	100
	0 – 40	49.1	100
Spring green manure (oil radish, white mustard, peas)	0 – 20	54.1	127.3
	20 – 40	64.0	114.9
	0 – 40	59.0	120.2
Sowing grasses	0 – 20	60.0	141.2
	20 – 40	68.7	123.3
	0 – 40	64.4	140.9

Oilseed radish, together with white sweet clover and spring rape, provided 59-63% of agronomically valuable aggregates and 33–40% of water-resistant aggregates, which is close to the optimal parameters of these indicators for chernozem soils (Table 3.46).

Table 3.46

Influence of different green manure crops on the composition of soil aggregates in the 0-30 cm layer at the end of buckwheat growing season, % (Zubets, 2004)

Variant	Вид аналізу	Fraction size, mm									10 – 0,25 mm %
		>10	10-7	7-5	5-3	3-2	2-1	1-0,5	0,5-0,25	<0,25	
Without green manure (control)	Dry sieving (A)	28	8	7	8	6	14	6	7	16	56
	Wet sieving (B)			2.4	2.0	1.8	2.3	6.6	15.6	69.3	30,7
Phacelia	Dry sieving (A)	26	9	8	8	8	11	6	8	16	58
	Wet sieving (B)			1.1	1.9	1.9	2.1	9.8	14.7	68.5	31,5
White sweet clover	Dry sieving (A)	24	10	9	8	7	14	7	8	13	63
	Wet sieving (B)			1.2	1.0	1.6	6.9	10.0	18.3	61.0	39,0
Spring rape	Dry sieving (A)	23	9	9	9	7	15	7	8	13	64
	Wet sieving (B)			1.5	1.2	1.6	7.7	10.2	17.4	60.4	39,6
White mustard	Dry sieving (A)	25	9	8	9	8	12	6	7	16	59
	Wet sieving (B)			1.5	1.2	1.8	5.4	7.0	17.0	66.1	33,9
Oilseed radish	Dry sieving (A)	24	10	8	9	7	12	6	8	16	60
	Wet sieving (B)			1.7	1.5	1.7	3.4	7.2	17.2	67.3	32,7
F_f(A)		87.5*								60.9*	172.1*
LSD_{05} (A)		0.74								0.43	1.67
F_f (B)										123.7*	98.6*
LSD_{05} (B)										1.74	0.98

* $F_f > F_{table}$

Research by Narusheva (2018) also showed that green manure increased the activity of ammonifying and nitrifying groups of microorganisms, resulting in an increase in the concentration of available forms of ammonium and nitrate nitrogen in the soil. The green mass of the studied green manure is rich in nitrogen and has a narrow carbon to nitrogen ratio of 10:1–12:1, which contributed to the mobilization of nutrients in the topsoil. The use of green manure, in addition, increased the content of nitrate ($N–NO_3$) and ammonium ($N–NH_4$) nitrogen in the soil, respectively, by

0.8–4.6 and 7.5–15.2 mg kg^{-1} (oil radish in particular by 3.1 and 9.6 mg kg^{-1} (Table 3.47). Moreover, a positive trend in the concentration of these forms of nitrogen was observed in the third year after the application of these green manure.

Table 3.47

Effect of green manure on the content of nitrate and ammonium nitrogen in the layer 0 – 30 cm at the end of the growing season (Narusheva, 2018)

Variant	Nitrogen content in the 0–30 cm layer, mg kg^{-1} soil		
	$N\text{-}NO_3$	$N\text{-}NH_4$	Nitrogen amount
Without green manure (control)	6.1	11.2	17.3
Phacelia	6.9	18.7	25.6
White sweet clover	10.7	26.4	37.1
Spring rape	10.4	25.6	36.0
White mustard	9.5	25.3	34.8
Oilseed radish	9.2	20.8	30.0
LSD_{05}	0.24	0.61	0.86

The content of mobile forms of phosphorus and potassium in the soil also tended to increase with the use of green manure due to organic acids – root secretions of green manure. The use of oil radish contributed to an increase in phosphorus availability by 2.5–3.5% and potassium by 1.5–1.8% over a three-year cycle. The indicators of soil "breathing" also increased – the release of carbon dioxide was 15–18% higher when oil radish was planted than in the variant without green manure. Under the same conditions of the study, the water regime improved when plowing green manure, in particular, water retention and water-raising capacity, and the enzymatic activity of the soil increased (Table 3.48)

Karpenko (2002) found that the use of oil radish as a green manure for corn under different tillage systems had a positive effect on the dynamics of Nitrogenobacterium, as well as non-spore bacteria, actinomycetes and fungi. The presence of Azotobacter in the soil is an indicator of its fertility, as it is an indicator of the presence of phosphorus, potassium, calcium, pH, etc. in the soil. This microorganism has the ability to fix atmospheric nitrogen and synthesize plant growth stimulants such as auxin and vitamins. The author's experiments have shown that the use of oil radish increases the number of nitrogenase in the phase of 6-8 leaves of corn, which indicates its high biological activity. Under these conditions, a higher amount of nitrogen bacteria is observed in shelf cultivation than in chisel cultivation. This dependence was observed before harvesting corn in the variant with manure application and the use of oil radish for green manure and green fodder, while the amount of nitrogen bacteria decreased under chisel tillage (Table 3.49).

Table 3.48

Effect of green manure on the activity of soil enzymes under buckwheat sowing (Narusheva, 2018)

Variants of the experiment	Enzyme activity			
	urease, mg urea/ 10 g soil/day	amylase, mg maltose/ 10 g soil/day	xylanase, mg/1 ml of reaction mixture	invertase, mg glucose/ 1 g soil/4 h
Without green manure (control)	107	12.2	7.26	16.0
Phacelia	128	21.4	7.74	24.2
White sweet clover	151	25.0	8.80	18.8
Spring rape	144	28.5	9.10	32.8
White mustard	135	23.8	8.40	28.6
Oilseed radish	135	26.9	8.10	27.2
LSD_{05}	3.4	0.5	0.2	0.6

It has also been found that the use of oil radish as a green manure contributes to an increase in glycine, aspartic and glutamic acids in the soil, which is evidence of an increase in soil biological activity and the intensification of positive microbiological processes, especially expressed in the background of chiseling. The positive effect of oil radish on the soil bulk was also noted. Its use as a green manure provided the lowest soil density among all studied variants 1.05 –1.22 g cm^{-3} with lower values on the background of plowing (Table 3.50).

Table 3.49

Influence of non-humified organic matter and different tillage methods on the allelopathic activity of soil under maize (% fouling of soil lumps with Azotobacter culture), % (Karpenko, 2002)

Variants	Plowing by 28 to 30 cm			Chisel cultivation by 28 to 30 cm		
	before sowing	phase 6 leaves	before the harvest	before sowing	phase 6 leaves	before the harvest
Control (root and stubble residues of winter wheat)	98	96	98	96	94	98
Manure, 40 t ha^{-1}	100	100	100	94	98	98
Winter rape for green manure	92	100	94	98	96	96
Winter rape for green fodder	96	100	98	100	100	96
Oilseed radish for green manure	96	100	100	96	100	98
Oilseed radish for green fodder	96	100	100	96	100	98

Oil radish also had a positive effect on the soil nutrient regime: the amount of hydrolyzed nitrogen in the soil and the content of mobile forms of phosphorus and potassium increased, especially under chisel cultivation (Table 3.51).

The conclusions of various researchers were confirmed by Perchuk (2008). The author argues that oilseed rape plays a leading role in terms of its impact on density reduction. This crop can be attributed to crops that can contribute to the loosening of the topsoil, which is an obstacle to the active penetration of moisture, air and plant roots (Table 3.52).

Thus, the introduction of green manure and green manure under the main tillage leads to a tendency to reduce the volume mass of the soil, both before sowing crops and during harvesting. The decrease in soil density due to the use of green manure is associated with a faster decomposition of the organic mass of green fertilizers.

Table 3.50

Influence of primary tillage and post-harvest crops on the dynamics of active soil layer density in corn crops, g cm^{-3} (Karpenko, 2002)

Variants	Soil cultivation					
	Plowing by 28 to 30 cm			Chisel cultivation by 28 to 30 cm		
	before sowing	phase 6 leaves	before the harvest	before sowing	phase 6 leaves	before the harvest
Control (root and stubble residues of winter wheat)	1.07	1.15	1.20	1.10	1.22	1.27
Manure, 40 t ha^{-1}	1.06	1.14	1.18	1.08	1.22	1.25
Winter rape for green manure	1.05	1.12	1.18	1.08	1.20	1.24
Winter rape for green fodder	1.06	1.15	1.18	1.09	1.21	1.25
Oilseed radish for green manure	1.05	1.11	1.17	1.06	1.17	1.22
Oilseed radish for green fodder	1.06	1.14	1.18	1.08	1.19	1.22

The author (Perchuk, 2008) notes that the application of different types of organic fertilizers reduced the degree of soil fracture, which thereby depended on the amount of organic matter supplied with fertilizers. The highest value of this indicator was observed in variants using green mass of post-harvest oil radish crops. The peculiar and quite useful work of its vertical-taproot systems is that penetrating with powerful roots deep into the depths, beyond the arable layer, it leaves behind a network of corresponding passages that carry out vertical soil drainage. As a result, favorable water and air regimes are created not only in the topsoil, but also in the subsoil. These moves facilitate the penetration of gravity water into the depths and accelerate the process of enriching the subsoil layers with humus.

The use of oil radish increased the slotting of the topsoil by 2–6%. The best slotting is created with the use of shelf cultivation with a general positive trend of green manure influence on the change of this physical indicator.

The moisture availability of the topsoil in the variants using different types of organic fertilizers was on average 1.0–2.5% higher than in the control variant within the tilth layer, which is explained by the general improvement of the main agrophysical parameters of the soil, as well as the influence of the green mass of oil radish as a mulching material and organic matter, which reduces unproductive moisture losses.

Table 3.51

Influence of non-humified organic matter and different methods of basic tillage on the dynamics of exchangeable phosphorus and potassium content in soil under maize crops, mg per 100 g of dry soil (Perchuk, 2008)

Variants	Plowing by 28 to 30 cm						Chisel cultivation by 28 to 30 cm					
	before sowing		phase 6 leaves		before the harvest		before sowing		phase 6 leaves		before the harvest	
	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
Control (root and stubble residues of winter wheat)	17.07	2.07	17.14	17.3	17.02	13.3	17.70	20.2	17.40	17.1	17.53	13.9
Manure, 40 t ha^{-1}	18.52	23.8	19.37	19.3	20.07	14.8	19.00	23.2	19.60	18.0	19.26	15.7
Winter rape for green manure	17.23	23.0	17.66	17.3	17.85	14.6	18.43	21.8	19.25	18.3	17.82	16.7
Winter rape for green fodder	16.18	21.8	16.96	14.7	16.72	13.5	15.7	21.2	16.78	17.5	16.12	15.1
Oilseed radish for green manure	18.82	22.5	17.38	18.7	17.66	14.7	-	21.9	20.96	19.1	20.05	17.1
Oilseed radish for green fodder	14.71	20.5	16.78	15.7	16.98	14.0	15.94	21.5	17.15	17.2	16.90	15.3

The data indicate that the best conditions for moisture availability were formed in variants with shelf basic tillage at 25-27 cm against the background of the use of oil radish green manure (Table 3.53). Plowing oil radish into the soil increases the content of water-resistant aggregates and the slit content in the tilth layer of the soil, which leads to a more even distribution of precipitation profile and better water absorption.

The results of the research by Perchuk (2008) showed that the content of phenolic compounds in the soil depends on the type of organic green manure and the main soil tillage (Table 3.54).

Table 3.52

Influence of green manure and basic tillage on the volume mass of topsoil 0-30 cm, g/cm3 (Perchuk, 2008)

Variant	Observation period					
	during sowing		6 to 8 leaves		during harvesting	
	g cm^3	%	g cm^3	%	g cm^3	%
Plowing by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	1.18	100	1.27	100	1.35	100
Manure – 40 t ha^{-1}	1.13	96	1.18	93	1.21	90
Oilseed radish	1.10	93	1.17	92	1.20	89
Oats + peas	1.12	95	1.19	94	1.20	89
Straw – 4 t ha^{-1}	1.15	97	1.22	96	1.24	92
Chisel cultivation by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	1.19	100	1.25	100	1.34	100
Manure – 40 t ha^{-1}	1.15	97	1.20	96	1.22	91
Oilseed radish	1.12	94	1.18	94	1.20	89
Oats + peas	1.15	97	1.20	96	1.21	90
Straw – 4 t ha^{-1}	1.18	99	1.20	96	1.25	93
LSD_{05}	0,03		0,03		0,06	

The total content of phenolic compounds in the soil depended solely on the amount of green manure applied and the degree of its decomposition. The mass of oil radish plants underwent the process of decomposition most actively during the second term of determination – in the phase of formation of 6–8 leaves of corn.

When assessing the shelf and non-shelf tillage, and, accordingly, the method of green manure and green manure, almost the same tendency of decomposition of non-humified organic matter and release of phenolic compounds was noted. However, their amount is higher when using the shelf method of basic tillage with the simultaneous introduction of oil radish as a post-harvest green manure.

The study of methods of soil cultivation and green manure cultivation in the aisles of the orchard, as well as their impact on the physical and biological properties of the soil and productivity of apple trees was carried out in the educational and research garden of Podilsky State Agrarian and

Technical University (Table 3.55), it was found that the best option for maintaining the soil of an apple orchard of an intensive type of plantations for the conditions of the southwestern part of the Forest-Steppe of Ukraine is tillage to a depth of 5–6 cm in combination with the cultivation of oil radish, which increases soil fertility with simultaneous improvement of its agrophysical properties and ensures high productivity of apple plantations (Pecheniuk et al, 2017).

Table 3.53

Influence of green manure and main tillage on moisture content of 0-100 cm soil layer, % (Perchuk, 2008)

Variant	Observation period					
	during sowing		6 to 8 leaves		during harvesting	
	%	% to control	%	% to control	%	% % to control
Plowing by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	23.5	100	22.1	100	19.7	100
Manure – 40 t ha^{-1}	24.2	103	23.0	104	20.2	103
Oilseed radish	25.8	109	23.7	107	21.5	109
Oats + peas	24.0	102	22.5	102	20.8	105
Straw – 4 t ha^{-1}	23.8	101	21.5	97	20.0	101
Chisel cultivation by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	22.6	100	21.3	100	18.5	100
Manure – 40 t ha^{-1}	23.3	103	22.2	104	19.3	104
Oilseed radish	24.6	109	22.8	107	19.8	107
Oats + peas	23.0	102	21.5	101	18.8	101
Straw – 4 t ha^{-1}	22.8	101	21.2	100	18.2	98

In the studies of Gudzia et al. (2011), it was proved that the use of post-harvest oil radish green manure, as well as the main tillage, directly affected the soil density under potato crops (Table 3.56). Thus, against the background of oil radish green manure, the volume mass of the tilthy soil layer decreased significantly – on average by 0.04 g cm^{-3} under both moldboardless tillage and plowing. And the share of green manure influence on soil moisture availability in potato cultivation was 41.2% (Table 3.57).

Under these conditions, the factor of green manure in the value of total potato productivity was 15.3%, and the yield on the background with green manure radish was 5.3 t ha^{-1} higher compared to the background without its use.

Table 3.54

Effect of green manure and main tillage on the content of phenolic compounds in the soil, mg/kg (Perchuk, 2008)

Variant	Observation period								
	during sowing			6 to 8 leaves			during harvesting		
	alcohol	water-acetone	total	alcohol	water-acetone	total	alcohol	water-acetone	total
Plowing by 25 to 27 cm									
Root and stubble residues of winter wheat (control)	5.7	25.7	31,4	4,5	30,5	35,0	10,0	26,5	36,5
Manure – 40 t ha^{-1}	8.4	31.5	39,9	6,0	34,3	40,3	15,0	30,1	45,1
Oilseed radish	7.4	36.7	44,1	7,0	37,7	44,7	17,3	38,0	55,3
Oats + peas	6.0	26.6	32,6	5,1	30,8	35,9	11,0	31,0	42,0
Straw – 4 t ha^{-1}	6.5	26.5	33,0	4,1	29,0	33,1	10,3	27,0	37,3
Chisel cultivation by 25 to 27 cm									
Root and stubble residues of winter wheat (control)	4.9	20.3	25,1	5,0	26,4	31,4	8,7	23,3	32,0
Manure – 40 t ha^{-1}	7.0	26.5	33,5	6,3	33,2	39,5	11,4	25,8	37,2
Oilseed radish	8.2	28.5	36,7	7,7	36,7	44,4	15,5	32,5	48,0
Oats + peas	5.1	11.7	26,8	5,3	27,0	32,3	10,3	24,7	35,0
Straw – 4 t ha^{-1}	5.4	20.5	25,9	4,7	25,5	30,2	7,8	24,0	31,8
LSD_{05}	1.2	6.7		1,1	4,5		3,1	4,5	

There is a high positive role of oil radish as a component of biological compatibility when grown together with most vegetable crops (Table 3.58), and as a green manure for growing vegetable crops in comparison with other green manure crops and mulching. For example, according to Bublik (2013), carrot yields after oil radish green manure were twice as high as when mulch was used as a control and significantly higher than when vetch and phacelia were used as green manure.

Table 3.55

Structural composition of soil depending on the methods of its cultivation in the garden aisles and green manure cultivation (Pechenyuk et al., 2017)

Methods of soil cultivation	Greem manure	Soil layer 0–60 cm			
		> 10	10 – 0,25	< 0,25	structural coefficient
Plowing 20–22 cm	Without green manure (control)	21.11	75.06	3.8	3.01
	Spring rape	18.94	79.38	2.9	3.63
	Oilseed radish	17.77	79.31	2.9	3.83
Disking 10–12 cm	Without green manure (control)	20.78	75.01	4.2	3.00
	Spring rape	18.92	77.57	3.5	3.46
	Oilseed radish	19.13	77.76	3.1	3.50
Milling 5–10 cm	Without green manure (control)	19.51	77.02	3.4	3.36
	Spring rape	18.09	79.16	2.8	3.78
	Oilseed radish	17.15	80.06	2.7	4.03

Table 3.56

Influence of main tillage methods and green manure background on bulk mass in 0-30 cm soil layer during potato cultivation, g cm^{-3} (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of primary tillage (factor B)			
	plowing 28 –30 cm	shelfless 28–30 cm	shelfless 13–15 cm	shelfless 6–8 cm
Without green manure	1.20	1.18	1.21	1.21
Post-harvest green manure (oilseed radish)	1.15	1.13	1.17	1.18
LSD_{05} 0.017. factor A 0.009. factor B 0.012				

Table 3.57

Influence of methods of main tillage and green manure on productive moisture reserves in 0-30 cm soil layer during potato cultivation, mm (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of primary tillage (factor B)			
	plowing 28 –30 cm	shelfless 28–30 cm	shelfless 13–15 cm	shelfless 6–8 cm
Without green manure	30.4	32.2	31.7	32.5
Post-harvest green manure (oilseed radish)	32.7	34.7	33.4	34.8
$LSD_{05\ зас}$ 1.02. factor A 0.51. factor B 0.72				

Table 3.58

Compatibility of oilseed radish with main vegetable and berry crops (Bublyk, 2013)

Crops	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Eggplant																			+		
2. Vegetable bean						*		*	–		+		*							–	*
3. Grape					–	+			–				+						+		
4. Pea									–	+	+	*	*	*			–		–		
5. Cabbage			–			*			*		*	–	–	+	*	+	*		+		*
6. Potatoes		+			*			*					*	*		–			+		+
7. Strawberries					*	*			*			+	*	*	*				+	*	+
8. Corn		+									+			+	–	–	+	*	+		
9. Onion		–		–			*			+			*	*	*				–		*
10. Carrot				+					+				*	*			*			*	+
11. Cucumber		+			*			*	*				*	*	*	*			*	*	*
12. Parsley				*			*						*	*		*	+				
13. Radish, radish, oilseed radish, daikon, lobo				*	–	*	*		*	*		*	–	+	*		*		+	*	*
14. Lettuce				*	+		*		*		*		+				*		*	*	*
15. Beetroot					*		*		+		*		*	*	+	+			+	*	+
16. Celery					+	–		–	*	–		–		*	*		*			+	*
17. Tomato					*				*	*		+	*	*	*	*			*	*	*
18. Pumpkin								*													
19. Beans				–	+	+	*	+	–		+		+	*	+	+	+			–	+
20. Garlic				–	–		*			*	*				*		*		–		
21. Spinach					*	+	*		*	*		*	*	*	+	*	+		+		

+ – very good compatibility; * – good compatibility; – - poor compatibility.

Today, oil radish is also an active component of biological farming. Thus, according to Shuvar (1994, 1997, 2003, 2005, 2014), green manure crops can compensate for the negative impact of intensive agricultural production on its quality and the environment, and provide a deficit-free balance of humus in soils, acting as an alternative to organic fertilizers. In his proposed scheme – a model of biological farming (organic fertilization system), presented below, green manure from three crops – oil radish, white mustard and winter rape – are the key components.

Organic fertilization system (model of biological farming) for rotational crop rotations:

1) vetch–oat mixture – $N_{20}P_{30}K_{30}$ + post–harvest oil radish – N_{30} (during sowing); 2) winter wheat – 20 t ha^{-1} of oil radish green manure + $N_{15}P_{40}$; post–harvest white mustard – 3 t ha^{-1} of straw + N_{15} (for wrapping with straw) + N_{40} (during sowing); 3) potatoes – 55 t ha^{-1} of manure + 20 t ha^{-1} of white mustard or oil radish green manure + $N_{20}P_{40}K_{40}$; 4) spring barley – P40 + post–harvest winter rape – 3 t ha^{-1} of straw + N_{15} (for hilling with straw) + $N_{20}P_{30}K_{30}$ + N_{30} (spring fertilization); 5) corn for silage – 55 t ha^{-1} of manure + 30 t ha^{-1} of winter rape green manure + $N_{30}P_{60}$.

Confirmation of the effective role of oil radish in the system of biological farming, even on relatively poor soils, is a study that examined the effectiveness of the use of oil radish green manure on their impact on the yield of a number of crops (potatoes, spring barley) and on soil quality and fertility (Table 3.59). It was found that biological indicators of soil fertility are closely related to the amount of green mass of plowed oil radish green manure, which is not inferior to narrow–leaved lupine and is close to increased doses of cattle manure. Both oil radish and white mustard green manure increase yields and improve crop quality both in the first crop of the rotation and in the first year afterwards, with oil radish being more effective than white mustard.

The research studied the variants of oil radish without fertilizers, oil radish + background ($P_{90}K_{90}$), oil radish + background + N_{60}, oil radish + background + N_{120}, oil radish + background + N_{180}. In all the studied variants of the experiment, a close direct correlation was observed between the yield of potatoes and barley (r = 0.929–0.996), the intensity of soil respiration and the amount of green manure incorporated into the soil (r = 0.835–0.920). Moreover, this relationship is manifested both by the effect of green manure and its aftereffect.

The intensity of soil respiration, which was estimated by the amount of CO_2 released from the soil in terms of kg/ha per hour. Depending on the variant of oil radish use, this indicator was in the range of 2.0–3.3 kg ha^{-1} per hour and was significantly higher than that of mustard, approaching the equivalent of using 20 t ha^{-1} of cattle manure. The respiration intensity of direct use of oil radish green manure was 25–40% higher.

The analysis of the conditional balance of mineral nutrients in the crop rotation link, both with direct and combined use of oil radish, showed that the studied variants have a positive balance of all three macronutrients under study – nitrogen, phosphorus and potassium. Moreover, the relative balance before the removal of mineral nutrients for three years was: N – 148 – 155 %, P_2O_5 – 256 – 283 %, K_2O – 160 – 165 % with combined and N – 147 – 159 %, P_2O_5 – 270 – 331 %, K_2O – 163 – 171 % with direct use of green manure. At the same time, the calculations showed that when using oil radish as a green manure (combined use), depending on the variant of the experiment, N – 30–70, P_2O_5 – 10–30, K_2O – 40–70 kg ha^{-1} were introduced into the soil. With direct use, these values were higher and amounted to N – 50–110, P_2O_5 – 30–50, K_2O – 60–150 kg ha^{-1}, which is equivalent to the application of 10–22 t ha^{-1} of cattle manure. The conditional balance of nutrients (N, P, K) was higher with the direct use of green manure compared to the combined application by an average of 10–20%.

The balance of humus in the green manure-potato-barley crop rotation was negative in all variants. However, with the direct use of oil radish, it was close to deficit-free. A positive humus balance was observed only in the variant with cattle manure of 40 t/ha. With the combined use of green manure, the humus balance indicators for all crops were lower than with its direct use. This is due to both lower doses of plowed green mass than with single mowing and the use of the first mowing crop for fodder purposes.

The maximum yield of potatoes with direct use of green manure was in the variant "oil radish + Fon + N_{180}" and amounted to 29.5 t ha^{-1}, while with the combined use of the same variant it was 23.2 t ha^{-1}. In general, the yield of potatoes with direct use of green manure was higher than with the combined one by an average of 2.0–5.0 t ha^{-1} or by 5–15%.

Table 3.59

Dependence of yield and soil respiration rate on the amount of plowed green manure – oilseed radish (Kiselev, 2012)

Indicators	Direct use of green manure		Use of the 1st mowing for fodder, the second for green manure (combined)	
	regression equation	correlation coefficient	regression equation	correlation coefficient
The amount of plowed green manure and potato yield after its application	y = 0.209x + 177.7	0.996	y = 0.088x + 206.8	0.920
The amount of plowed green manure and the yield of spring barley in the aftermath of its application	y = 0.006x + 20.85	0.946	y = 0.012x + 19.19	0.893
The intensity of soil respiration under potatoes and the amount of green manure plowed (direct effect)	y = 0.002x + 1.452	0.929	y = 0.006x + 0.962	0.906
The intensity of soil respiration under spring barley and the amount of green manure plowed (aftereffect)	y = 0.002x + 1.266	0.974	y = 0.007x + 0.3	0.835

The same studies (Kiselev, 2012) found that starting from a nitrogen dose above N_{60}, the yield of oil radish green mass exceeded the MPC for nitrates by 2.5–3 times. Therefore, the dose of nitrogen for fodder purposes and in the combined use of oil radish as a green manure should not exceed 60 kg ha^{-1}, which confirms our conclusions about the peculiarities of fertilizing oil radish when it is grown for fodder purposes.

It is important to note that the experience of the so-called “green mulching” is widely used, especially in European countries. Most often, lupine, oil radish, white mustard, alfalfa, horse beans, sainfoin, clover are used. As mulch, the mowed green mass is scattered on the soil surface, but a greater effect can be obtained by mixing it with the topsoil with disk tools.

Another important factor in the importance of oil radish as a phytomeliorant is its use as a green manure on radioactively contaminated soils. Chernilevsky et al. (2003) note that oil radish can be effectively used even on sod-podzolic soils with a cesium contamination density of more than 5 Ci km^{-2} due to low values of radioactive isotope transfer coefficients into the plant (Table 3.60).

Table 3.60

Transition coefficients (TC) of Cesium-137 from sod-podzolic soil to different types of fodder crops (Chernilevsky et al., 2003)

Fodder crops (leaf and stem mass)	Conversion rate (CR)*	Fodder crops	Conversion rate (CR)
Kostrytsa	0.02	Barley	0.10
Visianytsia	0.05	Oats	0.10
Tymofiivka	0.05	Paisa	0.20
Collective bentgrass	0.20	Mallow	0.30
Meadow foxtail	0.32	Vetch	0.21
Fierce	0.10	Vetch	0.30
Oilseed radish - green mass	0.20	Alfalfa	0.50
- seeds	0.30	Clover	0.50
Rapeseed	0.40	Sweet clover	1.20
Fodder cabbage	0.70	Amaranth	1.50

PC* – proportionality (transition) coefficient, (Bq kg^{-1})/(kBq m^{-2}).

Due to the low values of the conversion coefficient, oil radish is recommended as an annual organic ameliorant to reduce the accumulation of radioactive isotopes (in particular, cesium) in crop products by 1.2–1.5 times.

Thus, oil radish should be recommended in biological systems of technologies aimed at restoring the fertility of disturbed lands, providing green manure fertilization systems in various cultivation systems, and as an active and effective phytosanitary of the field.

According to the research of Klymenko et al. (2001), the biological activity of soils largely depends on the application of fertilizers, primarily organic fertilizers. The use of mineral fertilizers does not lead to an increase in most indicators of soil biological activity, and also negatively affects the development of microorganisms. Only an organic-mineral fertilizer system provides a sustainable increase in soil biogenicity and positive changes in the species composition of microorganisms: the number of nitrogen-fixing bacteria increases. Physical processes in the soil are extremely important for soil fertility. Mineral fertilizers have been shown to stimulate crop development by increasing the content of organic matter in the soil and thus indirectly affecting its physical properties. Organic fertilizers have a direct effect on soil physical properties, improving them

It has been established that green manure affects the allopathic activity of the soil. Thus, the study of the allopathic activity of the soil revealed that in the process of decomposition of the green mass of oil radish and white mustard in both concentrations, there is a stimulation of biotics, especially during the 2nd growing season. The joint use of green manure improved the allopathic state of the soil in the 2nd year of the experiment (Table 3.61).

Among the nonspecific organic substances of the soil, an important place is occupied by phenolic carboxylic acids, which can be formed during the decomposition of plant tissues by microbial degradation of lignin. They determine the degree of soil humification and are allopathically active substances (Grodzinsky, 1991; Blum, 2004). An increase in the content of phenolic carboxylic acids in the soil of the experimental variants by 1.2–1.7 times compared to the control 6 months after the introduction of unhumified organic matter was observed, mainly due to ferulic and coumaric acids (Pavliuchenko, 2011) (Table 3.62).

Table 3.61

Allelopathic activity of the soil at different doses of non-humified organic matter (watercress root growth, % to control) (M ± m) (Pavlyuchenko, 2011)

Variant	Number of months after application of organic matter					
	1	3	6	12	14	17
Soil + white mustard (5%)	117.9 ± 3.54	113.2 ± 3.40	84.3 ± 2.53	115.1 ± 3.45	116.1 ± 3.48	137.9 ± 4.14
Soil + white mustard (2,5%)	102.0 ± 3.06	112.6 ± 3.38	76.7 ± 2.30	120.8 ± 3.62	105.4 ± 3.16	137.9 ± 4.14
Soil + oilseed radish (5%)	112.6 ± 3.38	103.4 ± 3.10	89.9 ± 2.70	134.9 ± 4.05	154.4 ± 4.63	147.7 ± 4.43
Soil + oilseed radish (2,5%)	101.3 ± 3.04	107.5 ± 3.22	87.4 ± 2.62	131.1 ± 3.93	149.0 ± 4.47	134.1 ± 4.02
Soil + white mustard (2,5%) oilseed radish (2,5%)	93.4 ± 2.80	98.9 ± 2.97	86.2 ± 2.59	121.7 ± 3.65	127.5 ± 3.82	130.3 ± 3.91

Table 3.62

Phenolic carboxylic acids content in soil 6 months after application of non-humified organic matter, mg/kg (M ± m) (Pavlyuchenko, 2011)

Acid	Variant					
	Control (syringaria soil)	Soil + white mustard (5%)	Soil + white mustard (5%)	Soil + white mustard (5%)	Soil + white mustard (5%)	Soil + white mustard (5%)
Ferulova	6.4 ± 0.26	9.0 ± 0.36	8.6 ± 0.34	9.7 ± 0.39	10.1 ± 0.40	7.8 ± 0.31
p-Kumarova (trans-)	9.0 ± 0.36	14.0 ± 0.56	13.6 ± 0.54	14.5 ± 0.58	12.9 ± 0.52	11.3 ± 0.45
p-Coumarova (cis-)	5.3 ± 0.21	10.7 ± 0.43	10.1 ± 0.40	13.3 ± 0.53	9.8 ± 0.39	8.0 ± 0.32
o-Kumarova	7.0 ± 0.28	11.7 ± 0.47	9.0 ± 0.35	12.1 ± 0.48	10.8 ± 0.43	9.1 ± 0.36
Syringic	3.2 ± 0.13	5.8 ± 0.23	5.0 ± 0.20	4.7 ± 0.19	6.0 ± 0.24	4.0 ± 0.16
Vanillin	4.9 ± 0.20	6.6 ± 0.26	6.2 ± 0.25	7.1 ± 0.28	5.5 ± 0.22	5.1 ± 0.20
p-Oxybenzoic	4.7 ± 0.19	5.5 ± 0.22	5.7 ± 0.23	6.5 ± 0.26	6.4 ± 0.26	5.2 ± 0.21
Total	40.5 ± 1.62	63.3 ± 2.53	58.2 ± 2.33	67.9 ± 2.72	61.5 ± 2.46	50.5 ± 2.02

After 17 months of green mass decomposition, the amount of phenolic carboxylic acids in the soil decreased by 1.7–2.0 times. The content of coumaric acids decreased significantly. At the same time, the concentration of phenolic carboxylic acids in the control variant remained almost unchanged, which indicates the important role of green manure crops in the intensification of humus formation processes (Table 3.63).

This conclusion is confirmed by the results obtained in determining the humus content. The introduction of unhumified organic matter of white mustard and oil radish in different doses contributed to a gradual increase in its content by 10-40% compared to the control.

Reducing the phytotoxicity of syringaria soil under the influence of green manure affected the physiological state of plants, in particular the content of the main photosynthetic pigments, and growth processes.

An increase in the content of chlorophylls a and b and carotenoids in the leaves of seedlings was noted a month after the introduction of organic matter. After 17 months, the best results were obtained in variants with separate application of oil radish plant mass in doses of 2.5% and 5%.

The concentration of carotenoids in the leaves of seedlings in all experimental variants during the experiment significantly increased compared to the control (Table 3.64). Since carotenoids play an important role in the formation of protective mechanisms of the photosynthetic apparatus of plants (Taran, 1999; Vasyl'yeva, 1997), the increase in their content with the introduction of organic matter of green manure contributed to the increase of adaptive capacity of lilac to the action of the allopathic factor.

The growth of lilac seedlings was the highest in the variants with oil radish (2.5% and 5%) and exceeded the control values by 36–48%.

Table 3.63

Content of phenolic carboxylic acids in soil 17 months after application of unhumified organic matter, mg/kg (M ± m) (Pavlyuchenko, 2011)

Acid	Variant					
	Control (syringaria soil)	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**
Ferulova	7.5 ± 0.30	5.8 ± 0.23	6.5 ± 0.26	5.7 ± 0.23	7.1 ± 0.28	5.7 ± 0.23
p-Kumarova (trans-)	10.0 ± 0.40	9.0 ± 0.36	7.2 ± 0.29	9.1 ± 0.36	8.0 ± 0.32	6.2 ± 0.25
p-Coumarova (cis-)	4.4 ± 0.18	4.4 ± 0.18	3.1 ± 0.12	3.3 ± 0.13	3.8 ± 0.15	2.6 ± 0.10
o-Kumarova	6.0 ± 0.24	6.8 ± 0.27	5.0 ± 0.20	4.8 ± 0.19	5.6 ± 0.22	4.3 ± 0.17
Syringic	4.0 ± 0.16	2.8 ± 0.11	2.5 ± 0.10	3.1 ± 0.12	3.1 ± 0.12	2.5 ± 0.10
Vanillin	5.6 ± 0.22	4.5 ± 0.18	3.2 ± 0.13	4.5 ± 0.18	4.6 ± 0.18	3.2 ± 0.13
p-Oxybenzoic	3.6 ± 0.14	3.4 ± 0.14	2.7 ± 0.11	3.8 ± 0.15	3.6 ± 0.14	2.7 ± 0.11
Total	41.1 ± 1.64	36.7 ± 1.47	30.2 ± 1.21	34.3 ± 1.37	35.8 ± 1.43	27.2 ± 1.09

The use of non-humified organic matter of green manure crops, such as oil radish and white mustard, can be recommended as a means of improving the root soil and increasing the adaptive capacity of lilac plants in continuous long-term cultivation. The introduction of green mass of green manure helped to reduce the intensity of the allopathic soil regime during long-term lilac culture, which had a positive effect on the physiological processes of plants. The highest efficiency was found when applying oil radish in doses of 2.5% and 5% by weight of soil.

Table 3.64

Content of main photosynthetic pigments in leaves of lilac seedlings, mg% of crude matter (M ± m) (Pavlyuchenko, 2011)

Variant	Number of months after application of organic matter					
	1		6		17	
	chlorophyll	carotenoids	chlorophyll	carotenoids	chlorophyll	carotenoids
Control (syringaria soil)	242.0 ± 7.3	44.8 ± 1.3	248.0 ± 7.4	43.1 ± 1.3	239.7 ± 7.2	42.2 ± 1.3
Control (syringaria soil)	261.4 ± 7.8	52.0 ± 1.6	280.1 ± 8.4	51.8 ± 1.6	325.3 ± 9.8	55.4 ± 1.7
Control (syringaria soil)	249.5 ± 7.5	50.2 ± 1.5	275.2 ± 8.3	53.0 ± 1.6	306.9 ± 9.2	57.5 ± 1.7
Control (syringaria soil)	280.9 ± 8.4	55.2 ± 1.7	310.5 ± 9.3	59.0 ± 1.8	326.8 ± 9.8	61.7 ± 1.85
Control (syringaria soil)	253.0 ± 7.6	51.6 ± 1.6	300.2 ± 9.0	54.1 ± 1.6	311.8 ± 9.3	55.5 ± 1.66
Control (syringaria soil)	248.5 ± 7.5	47.3 ± 1.4	265.5 ± 8.0	49.0 ± 1.5	308.7 ± 9.3	50.4 ± 1.5

The positive formative role of different types of green manure on soil microbiological activity has been proven (Slavkina, 2019). The variants of the experiment in which the microbiological analysis was carried out were as follows: 1) no fertilizer (control); 2) white mustard + winter vetch; 3) oats + rapeseed + barley; 4) annual lupine; 5) oil radish; 6) oil radish + lupine.

Plowing green manure changed the content of soil organic matter, which, in turn, led to a change in the structure of the soil microorganism complex. The introduction of fresh organic matter into the soil increased its biogenicity by 15–40% (Table 3.65). Microorganisms that reproduce in the soil at the expense of organic matter of dead plant residues largely determine soil microbiological conditions for plant growth. Their activity determines the course of agronomically valuable processes in the soil, including the transformation of humus substances and the accumulation of mineral nutrients, primarily ammonia. In the studied variants, the number of ammonifying bacteria (NAB) was 1.5–4 times higher than in the control variant. An increase in the number of microorganisms that assimilate mineral forms of nitrogen (MN) was observed in the soil under a mixture of white mustard with winter vetch and annual lupine (plowing depth 15–18 cm). The activation of ammonifying and nitrifying microflora after plowing green manure crops ensured the supply of mineral nitrogen to the soil.

Due to the difference in the chemical composition of plant organic matter, the number of microorganisms in some cases increased due to different groups.

When plowing white mustard with winter vetch and annual lupine, the activity of ammonifying microorganisms, actinomycetes, and pedotrophs increased to a greater extent. An increase in the number of microorganisms of these groups provides a greater supply of mineral nitrogen to the soil. The joint application of slowly decomposing mustard components with a lightly hydrolyzed legume component – winter vetch – contributed to a faster assimilation of these organic substances by soil microorganisms and increased the rate of their mineralization.

After plowing a mixture of oats with rapeseed and barley, the number of fungi, ammonifiers, and oligonitrophiles increased. The high number of pedotrophic microflora (28.6 million per hectare of soil) and pedotrophicity coefficients (1.3–1.6) indicated enrichment of the soil with mobile organic matter and increased humus formation.

Due to the lack of nitrogen in the chemical composition of the green manure mixture, the decomposition of plant mass was restrained. This situation is unfavorable because microorganisms will replace the lack of nitrogen by mineralizing humus compounds. Therefore, after plowing green mass with a huge predominance of cereals, it is necessary to apply additional amounts of nitrogen fertilizers.

The fresh organic mass of green fertilizers stimulated the activity of cellulose-degrading bacteria (cellulose destruction reached 80–90%). Due to the activation of cellulose degraders, the supply of new carbohydrates to the soil increased. High cellulosic activity was observed for three years after the green manure was planted and contributed to maintaining a positive humus balance in the soil.

Table 3.65

The influence of green manure crops on the number and ratio of major and trophic groups of microorganisms in meadow-sod soil (thousand/ha of soil) (Slavkina, 2019)

Variant	Depth of earnings, cm	Bacteria	Actinomycetes	Mushrooms	Oligotrophs	Pedophiles	Total number of micro-organisms	The ratio of trophic groups		
								KAA MPA	Olig MPA	PA MPA
I experience										
Control 0–20 см		12733	4839	83.0	10869	13486	49547	1.1	0.9	1.0
20–40		9720	4720	97.0	9120	13280	45137	1.2	0.8	1.2
White mustard + winter mustard										
0–20 cm	15–18	55063	8063	83.0	25292	44666	164167	0.7	0.5	0.8
20–40 cm	25–28	12607	2397	77.0	14094	19592	57571	0.7	1.0	1.3
Oats + rape + barley 0–20 cm	15–18	17812	2155	78.0	14843	28625	76445	0.8	0.8	1.6
20–40 cm	25–28	16250	2125	250.0	19250	19500	68167	0.8	1.2	1.3
II experience										
Control 0–20 cm		21043	3068	121.0	12233	10069	51057	0.4	0.6	0.8
20–40 cm		8320	2000	74.0	7560	9720	47914	1.1	0.9	0.8
Oilseed radish 0–20 cm	15–18	11968	3136	58.9	32938	33110	90043	1.5	2.7	2.8
20–40 cm	25–28	6435	2117	37.3	12785	15240	40212	0.9	1.9	2.4
Annual lupine 0–20 cm	15–18	17466	6507	100.0	40784	44540	137390.0	2.0	2.3	2.6
20–40 cm	25–28	19234	5113	113.0	244544	38822	104464	1.1	1.3	2.0
Oilseed radish + lupine										
0–20 cm	15–18	18102	5796	147.0	39648	51828	130263	1.1	2.2	2.9
20–40 cm	25–28	12886	3328	134.0	25770	45568	99015	1.1	2.0	3.5

When oil radish, annual lupine and their mixture were used as green manure, the most effective effect on soil fertility was provided by annual lupine and joint application of oil radish with annual lupine.

Despite the high yield of green mass of oil radish, plowing this crop did not contribute to a noticeable increase in microbiological activity, the number of all trophic groups studied was low. The maximum humus content was observed after the annual lupine was embedded in the soil. The highest cellulosolytic activity was observed here, which is the main link in microbiological activity. The leading position of lupine in increasing the content of labile humus substances, despite the low yield of green manure, is associated with an increase in the soil of easily mobilized nitrogen compounds. The microbiological activity of the soil has increased significantly. A sufficient amount of nitrogen substances determined the most optimal mode of life of microorganisms in terms of humus formation.

A microbiological indicator of the intensity of humus formation processes is the indicator of microflora pedotrophicity. The highest coefficients of pedotrophicity were after plowing annual lupine and lupine together with oilseed radish (2.6–3.5). An increase in pedotrophicity by 1.5 times was observed after all green manure.

The increase in the total number of spore-forming bacteria, especially p. Bacsubtilis, the appearance of Bac. megaterium bacilli, the enrichment of the species composition of actinomycetes, oligonitrophils indicated an increase in mineralization processes and a more intense nature of the transformation of organic nitrogen and carbon in the soil after plowing green manure.

An increase in the total number of fungal microflora and its diversity indicated an improvement in carbohydrate balance. As a result of decomposition of plant organic matter in the soil, favorable nutritional conditions were created for the saprophytic fungus Trichoderma.

The decrease in the number of fungi p. Penicilium and p. Fusarium indicated an improvement in the phytosanitary situation in the soil.

The authors of the study (Slavkina, 2019) concluded that the impact of green manure biomass was manifested in an increase in the total number and species diversity of microorganisms, and enrichment of the soil with mobile organic matter. The most favorable microbiological regime was observed in the variant of white mustard + winter vetch, where the processes of nitrogen and carbon transformation were more balanced as the plant mass decomposed. The activation of the vital activity of all trophic groups of microorganisms after plowing green fertilizers created favorable conditions for the synthesis of organic matter.

The positive impact of green manure on a number of soil regimes was also noted in soil studies at Agroecology, where the green manure fertilization system is widely used.

The degree of supply of soil with mobile forms of phosphorus and potassium is very high against the background of low humus and mineral (ammonium) nitrogen content (Table 3.66).

The average content of humus and phosphorus in the soil after plowing mustard is somewhat lower than in the soil of the background variant, which is due to the data obtained from the analysis of the sample of the third elemental plot. At the same time, the availability of mobile potassium and ammonium nitrogen, on the contrary, is much lower in the background plot.

Table 3.66

Accounting of green mass yield of experimental crops, kg m^{-2} (Kharitonov and Shakhov, 2016)

Crop	Repeatability				On average
	1	2	3	4	
First sowing period					
Oilseed radish	2.06	2.15	2.04	2.06	2.08
White mustard	0.84	1.14	0.97	0.90	0.96
The second sowing season					
Oilseed radish	2.10	2.04	2.10	1.34	1.90
White mustard	2.23	2.55	2.29	2.61	2.42

The content of mobile potassium is the most stable, with only 4% variability. The most pronounced spatial heterogeneity of the site is in the content of mobile phosphorus compounds, with a strong variability of 46%. Moderate variability was observed in the content of organic matter (humus) and ammonium nitrogen in the soil – 22%. Thus, when mustard was plowed, there was a slight increase in the absorption capacity due to an increase in the amount of absorbed bases, as well as ammonium nitrogen and mobile potassium compounds.

The yield of green mass of oil radish averaged 2.08 kg m^{-2} (with a plot area of 3.14 m^2), which is 2.2 times higher than the yield of white mustard, or 11.2 t ha^{-1} (Table 3.67). It should be noted that the crop yields were very low even compared to the data obtained under production conditions. Accounting for the yield of green manure crops of the second sowing period showed that at late sowing dates, white mustard developed more actively, which provided a green mass yield of 2.42 kg/m^2 (plot area 1.57 m^2), which is 1.3 times higher than the yield of oil radish, and 5.2 t ha^{-1}. When assessing the total green mass of green manure incorporated into the soil, it should be borne in mind that re-sowing of crops was not carried out over the entire plot area, only on half of it. Accordingly, for variant 2, the average yield of green mass of white mustard and oil radish of the first mowing should be calculated based on the results of the fourth and third replication, and for variant 1 – the first and second replication (Table 3.68).

Thus, the amount of white mustard applied in variant 2 (two terms of sowing and embedding the crop in the soil) was 3.5 times higher than in variant 1 (one-time sowing of the crop); for oil radish, the difference between the variants was 1.9 times. The advantage of radish over mustard in variant 2 is less pronounced than in variant 1, the differences were 1.2 and 2.2 times, respectively.

The conditions for the growth and development of crops are not least determined by the physical and chemical characteristics of soils, and green fertilizers have a positive effect on them.

Evaluating the change in soil acidity, was note the following: according to the value of pH_{KCl} (exchangeable acidity), the soil can be characterized as slightly acidic. The double dose of green manure contributed to a slight decrease in acidity (by 0.1 pH units in the soil under mustard and by 0.05 – under radish), the soil under radish was slightly more acidic than under mustard. Similar changes were observed in hydrolytic acidity, which varied from 1.4 to 1.74 mg-eq 100 g^{-1} of soil.

At the same time, oil radish had a slightly greater positive effect than mustard on the amount of absorbed bases: after “smelling” one dose of fertilizer (green mass of the first sowing period), the difference was 0.7 mg-eq 100 g^{-1}, and a double dose (embedding the green mass of two mowing) – 1.2 mg-eq 100 g^{-1}. Thus, mustard influenced the change in soil acidity, and radish influenced the amount of absorbed bases, as a result of which the soil saturation with bases under both crops was equivalent and very high, increasing as the plant mass was added to the soil.

Table 3.67

The influence of siderates on the physical and chemical parameters of the soil (Kharitonov and Shakhov, 2016)

Variant	White mustard		Oilseed radish	
	"plowing" of the 1st term sowing	"ploughing" of two terms sowing	"plowing" of the 1st term sowing	"ploughing" of two terms sowing
C/humus, %*	1.04/1.79	1.07/1.84	1.09/1.84	1.30/2.24
pHкcl	5.10	5.20	5.05	5.10
$H_г$, mg–ekv/100 г	1.54	1.40	1.74	1.68
S, мг–екв/100 г	9.20	12.50	9.90	13.70
ЕКО, мг–екв/100 г	10.74	13.90	11.64	15.38
V, %	85.7	89.9	85.0	89.1

* in the numerator – carbon, in the denominator – humus (coefficient of conversion 1.724).

Table 3.68

The effect of siderates on the retention of available forms of nutrients (Kharitonov and Shakhov, 2016)

Indicator	White mustard		Oilseed radish	
	"plowing" of the 1st term sowing	"ploughing" of two terms sowing	"plowing" of the 1st term sowing	"ploughing" of two terms sowing
P_2O_5, mg kg^{-1}	158	150	138	151
$К_2O$, mg kg^{-1}	164	185	163	159
NH_4, mg kg^{-1}	4.5	4.5	9.0	5.5
NO_3, mg kg^{-1}	29.0	45.0	36.5	47.5
$N–NO_3$ + N–NH, mg kg^{-1}	10.0	13.7	15.2	15.0

The content of organic matter in the soil increased with the introduction of green mass, and its growth corresponded to the amount of plant mass that entered the soil: The minimum content of organic carbon was noted at the “flavoring” of mustard in the first term of sowing (1.79%), which is 0.05% less than when planting oil radish, and the maximum – at two-time cultivation and introduction of radish green mass into the soil (2,24%) when using mustard (by 20 mg kg^{-1}), and at a double dose (total application of green fertilizer of two sowing dates) was equivalent, and in the soil under mustard there was a slight decrease (by 8 mg kg^{-1}), and under radish – an increase (by 13 mg kg^{-1}). Other data were obtained taking into account changes in the content of mobile potassium compounds. Accounting for the amount of K_2O in the soil after a single application of green fertilizer showed the equivalence of crops, while with two applications under mustard, a significant increase in soil potassium availability was observed (by 21 mg kg^{-1}), while under radish the changes were insignificant with a downward trend.

The content of ammonium nitrogen in the soil under mustard did not change depending on the amount of green mass incorporated into the soil and was lower than in the soil after radish cultivation. The change in the amount of NH4 in the soil under radish was inversely related to the amount of planted green mass: with one-time planting, the amount of this form of nitrogen in the soil was 1.6 times higher than with two-time planting. The nitrate content varied from 29.0 to 47.5 mg kg^{-1}. As with ammonium nitrogen, a slightly higher amount of NO_3, especially when taking into account the content after plowing one dose of green fertilizer, was observed in the soil when planting oil radish, the difference with mustard was 7.5 mg kg^{-1}. With the introduction of a “double” dose of green manure, the differences decreased to 2.5 mg kg^{-1}, and the total nitrate content in the soil increased by 55 and 30%, respectively, when mustard and radish were “plowed” together.

The use of oil radish as a green manure ensured a greater accumulation of mineral nitrogen in the soil than mustard (by 5.2 and 1.3 mg kg^{-1}, respectively, for variants 1 and 2). At the same time, the stock of mineral nitrogen in the soil under this crop was practically independent of the dose, and when mustard was planted, it increased as the mass of plants introduced into the soil increased.

In the transitional zone of the southern Forest-Steppe – northern Steppe, previous studies have shown (Kolomiets et al., 2013) that after harvesting spring barley, using the optimal use of periods when favorable weather conditions prevail, green manure crops with a short growing season can be grown. Improving soil fertility is one of the main ways to increase agricultural production, save energy and preserve environmental sustainability. It is achieved mainly through mineral fertilizers and ameliorants in combination with agrotechnical measures. When applying chemicals, it is necessary to take into account their negative impact on the environment and toxicological and hygienic characteristics of plant products. In the current environment, the role of local organic fertilizers, which stabilize the humus content in the soil when applied systematically, is significantly increasing. To adapt green manure crops to the farming system, we studied the growth processes of green manure and their impact on sugar beet yields. Mineral fertilizer application rates for the crop were determined depending on the soil nutrient supply and the planned yield (Table 3.69).

The yield of green mass of sideral crops was in the range of 243–332 c/ha (Table 3.70). In terms of value, this can be equated to the application of 30 tons of manure/ha. A comparison of the yield of sugar beets grown on black steam, siderate and the variant with the introduction of a calculated dose of mineral fertilizer shows the feasibility of sideration, since the collection of root crops with mineral and organic fertilization amounted to 361 and 365 t ha^{-1}, respectively, the control (black steam) without fertilizer provided a lower yield level – 282 t ha^{-1} (Table 3.71)

Table 3.70

Fertilizer rates (kg/ha per year) for sugar beet depending on the height of the planned harvest and the availability of nutrients in the soil (Kolomiets et al., 2013)

Planned harvest, t ha^{-1}	The content of nutrients in the soil layer, mg per 100 g											
	nitrogen				phosphorus				potassium			
	0–10	10–15	15–20	20–25	2–5	5–10	10–15	15–20	2–4	4–8	8–12	12–18
250	75	50	40	25	70	55	30	10	65	55	40	25
350	105	75	55	30	100	75	45	15	95	75	55	30
450	135	95	70	40	125	95	55	20	120	95	70	40

Table 3.71

Yield of green mass of sideral crops, 2011–2012. (Kolomiets et al., 2013)

Sidereal culture	Productivity, c ha^{-1}		
	2010	2011	Average for 2010–2011
White lupine annual	284	298	290
Buckwheat	277	293	285
White mustard	237	249	243
Oilseed radish	329	335	332

Sugar beet is a moisture-loving crop, but at the same time, thanks to a powerful root system capable of extracting moisture from deep horizons, it is relatively resistant to drought. The presence of about 30–40 mm of moisture in the arable layer of the soil ensures friendly seedlings of beets (Table 3.72).

They consume the largest amount of water in July-August. 300–320 mm of moisture is needed during this period to obtain the maximum yield, and approximately 450–500 mm during the entire growing season. In general, sugar beets in the regions of the northern steppe and southern forest-steppe are provided with a sufficient amount of moisture during the entire growing season. The occupied steam has a higher supply of moisture, since the above-ground mass of plants prevents its evaporation, which explains the increase in the yield of root crops after fertilizing with siderates.

On the basis of the translated researches, its authors concluded that with a well-established organization of production in the zone of unstable and sufficient moisture in Ukraine, green fertilizers can become a reliable planned measure for returning nutrients to the soil, improving the phytosanitary condition of fields, reducing environmental pollution and reducing production costs in crop production. The introduction of siderable crops as an integral component in the system of organic or ecological agriculture will ensure the sustainable restoration of soil fertility and the desired quality of the obtained products.

One of the important agrophysical indicators of soil fertility and structure is porosity and the ratio of volumes of different pore sizes. Porosity determines water permeability, water-holding and mobility capacity, and evaporation of water from the soil. It has a direct impact on the formation of reserves of productive moisture in the soil, which determines the level of yield of cultivated crops. Porosity affects the moisture content and its infiltration into the lower layers of the soil. Pores provide soil drainage, contribute to the inflow of oxygen and the release of carbon dioxide, the growth and spread of roots. Indirectly, the pores affect the change in the mechanical properties of the soil, facilitate its cultivation.

Table 3.72

Sugar beet yield, 2011–2012, depending on the type of fertilizer (Kolomiets et al., 2013)

Variants	Yield. c ha^{-1}			Increase, c ha^{-1}	
	201	2012	Average for 2010–2011	to control	to mineral fertilizer
Control – without fertilizer (black field)	279	285	282	–	–
Application of mineral fertilizer ($N_{76}P_{88}K_{48}$)	352	370	361	79	–
White lupine annual	369	380	375	93	14
Buckwheat	364	378	371	89	10
White mustard	356	375	366	84	5
Oilseed radish	358	370	364	82	3

The most favorable soil water-air regime and conditions for the growth and development of plants are created under the conditions of its total porosity at the level of 50–60% of the total volume of the soil, non-capillary – 12.5–30 and capillary – 30–37.5% and the ratio between non-capillary and capillary porosity in the range from 1:1 to 1:3 (Krut, 1986). For normal growth and development of plants, prevention of oxygen starvation of the root system of plants in the soil, high capillary porosity should be ensured, and aeration porosity should be at least 15% from the total soil volume (Berezhnyak, 1998; Tikhonenko, 2009).

Experimental studies (Mishchenko, 2004) were conducted on the basis of the educational scientific and industrial complex of the Sumy National University, which is part of the Myrhorod-Sum agro-soil district of the Left Bank forest-steppe part of Ukraine.

The following options were included in the scheme of the field experiment:

– Control (return of harvest and stubble residues to the soil).
– Post-harvest cultivation for siderate of oil radish.
– Cultivation after harvest on siderate of phacelia pysmolystia.
– Post-harvest cultivation of seeded buckwheat siderate.
– Application of 25 t ha^{-1} of manure.
– Application of mineral fertilizers $N_{125}P_{63}K_{150}$.

Cultivation of post-harvest crops was carried out after harvesting grain ears from the beginning of August to the end of October. For sideration, oil radish of the Raiduga variety was used at the rate of 30 kg/ha and Phacelia Balo – 25 kg/ha, Ivanna buckwheat – 90 kg/ha.

Experiments were carried out on typical low-humus, medium-loam chernozem. The average annual amount of precipitation at the research site ranges from 550 to 480 mm. The duration of the growing season is 170–180 days on average. The average date of autumn frosts is October 4–6. The duration of the postharvest vegetation period is 80–90 days, with an amount of precipitation of 130–134 mm.

Long-term loosening of the soil is facilitated by the activation of its biological activity, which is ensured by the use of post-harvest crops on green manure. The root system of sidereal plants also carries out microdrainage of the arable layer of the soil, which improves its porosity (Table 3.73). Compared to the control without siderates, a significant increase in the total, capillary, non-capillary and porosity of aeration in the soil layer 0–30 cm was observed for the variants of the studied sideral crops: after oil radish, respectively, by 2.5–3.3%, 2.1–2.6 , 0.3–0.7 and 3.5–4.1%; in the variant of post-harvest phacelium per siderate by 1.3–3.7%, 1.3–2.5, 0.7–1.1 and 1.9–4.7%, respectively.

Among the soil horizons, according to all experimental options, the highest indicators of general, non-capillary, and porosity aeration were in the 0–10 cm soil layer, which is associated with higher looseness, a better pronounced structure, a greater presence of root remains, burrowing animal movements, etc. With the deepening of the soil horizons to 30 cm, there is a tendency to a certain decrease of these types of porosity: total by 0.4–5.1%, non-capillary – by 0.6–3.1%, and aeration – by 2.7–9.8% .

Capillary porosity was the highest in the 10–20 cm soil layer – 32.2–34.3%, which is associated with the destruction of capillaries in the 0–10 cm layer as a result of mechanical loosening. The smallest capillary porosity was in the soil layer of 20–30 cm, 30.9–33.2%.

In the soil layer of 0–30 cm, among the studied sideral crops, the highest porosity indicators were after oil radish and phacelia; compared to the control and buckwheat on siderate, the difference in these options was significant – in terms of total porosity by 2.9–2.4%, capillary porosity – by 2.4–1.4%, and aeration – by 3.7–3.1%. The porosity of the soil in the variants of the application of post-harvest sideral crops directly depended on the root mass formed by them.

In oilseed radish, a direct and close correlation was established between root mass and capillary and aeration porosity ($r = 0.82$ and 0.71) and an average correlation with total aeration porosity ($r = 0.4$). On the variant with buckwheat per siderate, there was a high correlation dependence only for aeration porosity ($r = 0.74$), and an average one for total ($r = 0.65$) and capillary ($r = 0.69$) porosity. In phacelium per siderate, the correlation dependence was medium for capillary porosity ($r = 0.64$) and aeration ($r = 0.59$), and weak for total porosity ($r = 0.29$).

Thus, oil radish turned out to be the best post-harvest crop for the optimization of porosity parameters.

It is known that the use of traditional organic fertilizer – manure, improves the porosity of the soil. The influence of sider crops on soil porosity remains an insufficiently studied issue. Therefore, the influence of siderates and traditional fertilizers on the formation of optimal soil porosity during the cultivation of sugar beets and potatoes was further investigated (Table 3.74).

Both under sugar beets and potatoes, the highest indicators of total (51.4–54.7%), capillary (26.6–31.7%), non-capillary (20.8–27.2%) and porosity aeration (20.9–28.0%) in all soil layers were on the option of applying oil radish for siderate.

The indicators of total (by 0.6–0.7%), capillary (by 0.3–0.4%) and aeration porosity (by 0.6–0.8%) were significantly lower than the best option for the option of using phacelia on siderate; general (by 0.5–1.0%), capillary (by 0.3–0.4% – when growing sugar beets), non-capillary (by 0.5–0.8% – when growing potatoes) (Table.) and aeration porosity (by 0.5–0.8%) for the application option of 25 t/ha of manure; all types of porosity – on the option of using buckwheat for siderate.

Table 3.73

Effect of post-harvest siderates on soil porosity, %
(average for 2000–2004) (Mishchenko, 2004)

Soil porosity	Soil layer, cm	Variant				LSD_{05}
		Control (without green manure)	Post-harvest green manure from oilseed radish	Post-harvest green manure from phacelia	Post-harvest green manure from buckwheat	
general	0–10	54.0	57.3	57.7	54.7	1.37
	10–20	53.6	56.1	56.4	53.7	1.25
	20–30	51.3	53.9	52.6	51.3	0.91
	0–30	52.9	55.8	55.6	53.2	1.10
capillary	0–10	31.2	33.8	33.7	32.1	0.83
	10–20	32.2	34.3	34.1	32.5	0.68
	20–30	30.9	33.2	32.2	31.4	0.40
	0–30	31.4	33.8	33.4	32.0	0.52
non-capillary	0–10	22.8	23.5	23.9	22.6	0.87
	10–20	21.4	21.9	22.3	21.2	0.65
	20–30	20.4	20.7	20.4	19.9	0.64
	0–30	21.5	22.0	22.2	21.2	0.68
aeration	0–10	33.5	37.6	38.2	34.1	1.57
	10–20	30.8	34.3	34.7	31.1	1.55
	20–30	26.5	30.1	28.4	26.6	1.18
	0–30	30.3	34.0	33.7	30.6	1.36

In general, the organic fertilizer variants resulted in an increase in all types of porosity compared to the control. The application of mineral fertilizers instead of organic fertilizers compared to the control led to a decrease in all types of porosity.

In the variants of sugar beet and potato cultivation with depth, there was a tendency to reduce the total soil porosity by 0.4–2.0%, non–capillary porosity by 0.1–1.2% and aeration porosity by 2.4–3.9%, which is associated with the illuvial process, in which products from the higher layers move to the lower ones, clog some pores and reduce the porosity of the lower horizons. In addition, the lower horizons of the soil are less structured.

Table 3.74

Influence of fertilizers and green manure on the porosity of soil horizons under sugar beet and potato, % (average for 2001–2005) (Mishchenko, 2004)

Option of fertilizer	Porosity, %											
	total			capillary			non-capillary			aeration		
	Шар ґрунту, см											
	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30
Sugar beet												
Control (without green manure)	51.7	51.3	50.1	30.4	30.9	30.0	21.3	20.4	20.1	25.7	22.9	20.1
Post-harvest green manure from oilseed radish	53.4	53.0	51.4	31.4	31.7	30.6	22.0	21.3	20.8	26.7	24.3	20.9
Post-harvest green manure from phacelia	52.8	52.3	50.7	31.0	31.3	30.2	21.7	21.0	20.5	26.1	23.6	20.1
Post-harvest green manure from buckwheat	52.0	51.6	50.3	30.7	30.9	30.0	21.4	20.7	20.3	25.6	23.1	20.0
Manure 25 t ha^{-1}	52.7	52.3	50.9	31.1	31.3	30.3	21.6	21.0	20.6	26.2	23.7	20.5
$N_{125}P_{63}K_{150}$	51.2	50.6	49.6	29.9	30.5	29.7	21.2	20.0	19.9	25.1	22.2	19.7
LSD_{05}	0.34	0.40	0.46	0.23	0.19	0.20	0.28	0.32	0.43	0.39	0.39	0.47
Potatoes												
Control (without green manure)	52.5	51.9	50.4	26.3	26.9	26.0	26.2	25.0	24.4	27.0	23.5	20.4
Post-harvest green manure from radish	54.7	54.0	52.0	27.4	27.7	26.6	27.2	26.3	25.4	28.0	24.9	21.0
Post-harvest green manure from phacelia	54.1	53.3	51.3	27.1	27.3	26.3	27.0	25.9	25.0	27.3	24.2	20.3
Post-harvest green manure from buckwheat	52.8	52.4	50.8	26.7	26.9	26.1	26.1	25.5	24.7	26.8	23.7	20.2
Manure 25 t ha^{-1}	53.8	53.0	51.4	27.3	27.5	26.4	26.5	25.5	24.9	27.3	24.1	20.5
$N_{125}P_{63}K_{150}$	51.9	51.3	49.8	25.9	26.5	25.7	26.0	24.8	24.0	26.3	22.8	19.9
LSD_{05}	0.61	0.62	0.37	0.33	0.27	0.27	0.62	0.50	0.35	0.34	0.46	0.43

The capillary porosity was also the lowest in the lower 20–30 cm soil layer. In the 10–20 cm soil layer, it was higher than in the upper 0–10 cm layer by 0.2–0.6%, which is due to the destruction of the vertical pores of the horizon during mechanical loosening when caring for sugar beet and potato crops. The dynamics of soil layer porosity of 0–30 cm under sugar beet and potato shows that the total porosity during the growing season decreased from 52.3–55.2 to 48.6–51.9 % and remained within optimal limits (> 50 %) only in the variants of plowing for green manure of post–harvest oil radish and application of 25 t/ha of manure.

The non–capillary porosity also decreased from 23.7–29.0 to 17.1–23.4 %, but did not exceed the optimal limits (12.5–30 %) for these crops.

The reason for its decline is the gradual compaction of the soil over time, which simultaneously contributed to an increase in capillary porosity from 24.7–30.2 to 26.1–32.5 %, which was within the optimal range (30–37.5 %) only when growing sugar beets using oil radish for green manure.

The porosity of aeration is related to the degree of soil loosening and moistening. At the beginning of sugar beet and potato cultivation in the soil layer of 0–30 cm, it was the highest – 22.6–25.8%, and in the middle of the growing season it decreased as much as possible (to 21.3–23.4%), and at the time of harvesting it increased to 23.1–24.7%, which is associated with a decrease in soil moisture reserves.

In all variants of nutrition backgrounds, the aeration porosity exceeded the limit of 15%.

When growing sugar beet and potatoes in the variant of using oil radish for green manure in the soil layer of 0–30 cm, the indicators of all types of porosity were the highest and closest to optimal (Table 3.75).

The total, capillary porosity (except for the variant of potato cultivation on the background of manure) and aeration porosity in the variants of using phacelia and 25 t/ha of manure for green manure were significantly lower than the best variant – by 0.6–0.9, 0.3–0.4 and 0.5–0.7%, respectively.

The use of oil radish and phacelia for green manure and the application of 25 t/ha of manure significantly exceeded the use of buckwheat for green manure and the control variant for all types of porosity of 0–30 cm of the soil layer. The variant of mineral fertilizers application in 0–30 cm soil layer significantly reduced the total, capillary and porosity of aeration compared to both the control and organic fertilizer backgrounds.

In our opinion, the increase in soil porosity under the influence of green manure and green manure is associated with an improvement in both soil structure and density.

This is due to an improvement in the intensity of micro– and mesofauna activity on the background of plowing radish and phacelia green manure and manure application, as evidenced by a close positive correlation between the structural coefficient and total soil porosity – r = 0.71–0.78; on the control and mineral fertilizer background, the correlation was of medium strength – r = 0.37 and 0.49.

The closest inverse relationship in sugar beet and potato crops was established in the variants of plowing post-harvest oil radish and phacelia for green manure between the density and total porosity of 0-30 cm of the soil layer – r = -0.98 and -0.99; it was slightly lower in the variants of buckwheat for green manure and the introduction of 25 t/ha of manure – -0.96 and -0.95, respectively.

The connection between the value of phytomass of post-harvest green manure crops and the total porosity and porosity of soil aeration is indicated by close and medium-density positive correlations.

The highest correlation between the amount of phytomass and total and porosity of aeration was found in the variant of growing oil radish on green manure – r = 0.66 and 0.73.

It was somewhat lower when using phacelia for green manure – r = 0.62 and 0.71 and the lowest in the variant of post-harvest buckwheat for green manure.

A positive and medium-density correlation was established between green manure phytomass and soil capillary porosity both in the cultivation of sugar beet and potatoes.

In the variant of using oil radish for green manure, the correlation coefficient was the highest when growing sugar beets (r = 0.52), and in the variant of using phacelia for green fertilizer – under potato crops (r = 0.55). In the variant of post-harvest buckwheat for green manure, the correlation coefficients were the lowest – r = 0.35 and 0.32. Thus, due to the improvement of soil structure and its density, the use of post-harvest green manure – oil radish – provided the most optimal indicators of total, capillary, non-capillary and porosity aeration for growing sugar beet and potatoes. Accordingly, the use of post-harvest green manure from oil radish, having the best indicators of soil porosity according to the results of the research, ultimately led to the highest yields of potato tubers of 30.9 t/ha and root crops of 36.6 t ha^{-1} (Table 3.76).

Table 3.75

Influence of fertilizers on soil layer porosity 0–30 cm under sugar beet and potato cultivation, % (average for 2001–2005) (Mishchenko, 2004)

Porosity, %	Mineral nutrition background						LSD_{05}
	control, without fertilizers	post-harvest green manure			Manure 25 t ha^{-1}	$N_{125}P_{63}K_{150}$	
		oilseed radish	phacelia	buck-wheat			
Sugar beet							
Total	51.0	52.5	51.9	51.3	52.0	50.5	0.34
Capillary	30.4	31.2	30.8	30.5	30.9	30.1	0.17
Non-capillary	20.6	21.3	21.1	20.8	21.1	20.4	0.28
Aeration	22.9	24.0	23.3	22.9	23.5	22.3	0.27
Potatoes							
Total	51.6	53.5	52.9	51.9	52.6	51.1	0.45
Capillary	26.4	27.2	26.9	26.5	27.0	26.1	0.27
Non-capillary	25.2	26.3	26.0	25.4	25.6	25.0	0.37
Aeration	23.6	24.6	23.9	23.6	24.0	23.0	0.23

Table 3.76

Effect of fertilizers on the yield of test crops, t ha^{-1} (Mishchenko, 2004)

Variants	Sugar beet		Potatoes	
	yield t ha^{-1}	increase, t ha^{-1}	yield t ha^{-1}	increase, t ha^{-1}
Control (without green manure)	30.0	–	24,8	–
Post-harvest green manure from radish	36.6	6.6	30,9	6,1
Post-harvest green manure from phacelia	35.2	5.2	29,3	4,5
Post-harvest green manure from buckwheat	31.3	1.3	25,7	0,9
Manure 25 t ha^{-1}	36.1	6.1	29,2	4,4
$N_{125}P_{63}K_{150}$	35.6	5.6	29,7	4,9
LSD_{05}	1.02		0.76	

During the analysis of soil porosity, it was found that the studied variants of post-harvest green manure had a significant increase in porosity compared to the control variant – plowing straw and post-harvest residues of winter wheat. Among the post-harvest green manure, oil radish had the advantage in porosity due to the highest yield of green manure, the root system of which contributed to the deepest soil drainage, and the wrapped phytomass – to the most intensive activity of soil biota, which resulted in improved soil structure and better soil loosening. Compared to an equivalent amount of manure, oil radish green manure also had a higher soil porosity during the period of sugar beet and potato cultivation. The background of mineral nutrition could not significantly compete with the variants of post-harvest green manure in terms of soil porosity, since this variant was inferior to the control one for the entire period of cultivation of row crops. Based on the above, we recommend to use post-harvest green manure of oil radish to improve soil porosity in the cultivation of sugar beet and potatoes.

It should also be noted that the importance of fertilizer biologization for the agricultural sector of Ukraine is an urgent issue of its successful implementation in the European space and allows to ensure the implementation of sustainable development goals in terms of ensuring food security of the state. Vinnytsia National University and the Uladovo–Lyulynetska breeding and research station as part of the All–Ukrainian Scientific and Educational Consortium are actively researching the issues of alternative fertilization systems, ensuring their environmental and soil protection component, transition to organic fertilization systems, development of regulations for the use of biofertilizers and biological products of growth–stimulating and growth–regulating nature within the framework of task 27. 00.02.01.F "To develop the scientific basis for biologization and improvement of fertilizer systems that increase crop productivity and stabilize soil fertility in the right–bank Forest–Steppe of Ukraine".

Our research was conducted in 2019–2020 simultaneously at the experimental field of VNAU and at the Uladovo–Lyulynets breeding and research station. The research site, the VNAU experimental field, is represented by dark gray forest soils. Agrochemical potential of the field: humus content: 2.02–3.2%, easily hydrolyzed nitrogen 67–92, mobile phosphorus 149–220, exchangeable potassium 92–126 mg/kg of soil at pHxl 5.5–6.0. The research format is small plot, replicated 3 times. The research site of the Uladovo–Lyulynetska breeding research station (laboratory for agricultural problems and stationary agrochemical research in the Western Forest–Steppe zone of Ukraine) is represented by deep low–humus leached chernozems of medium loamy mechanical composition. The humus content is 3.9–4.4%. The reaction of the soil solution is pH 5.9–6.3, the degree of saturation with bases is 86–91%. The content of easily hydrolyzed nitrogen is 99–115, mobile phosphorus is 119–159, and exchangeable potassium is 116–142 mg/kg of soil. The research format was small plot, replicated 3 times. The research program included the study of the impact of green manure crops application options, taking into account the peculiarities of their morphogenesis and phytomass formation, on certain soil properties, the level of weediness of the field after their application with an assessment of the yield of corn (winter wheat precursor).

The object of the study was used to compare the effectiveness of different green manure options using white mustard (Carolina variety), oil radish (Zhuravka variety) and spring rape (Diamant variety).

The sowing time for all green manure variants was in the middle of the second decade of July in 2018 and in the beginning of the third decade of July in 2019. The sowing of green manure was preceded by disking to a depth of 8–10 cm in two traces. The parameters of green manure agrocenoses design were formed on the basis of general methodological recommendations for intermediate green manure, taking into account the species characteristics of the green manure crop: sowing was carried out by the usual row (15 cm) and wide–row (30 cm) method with a planting density of 2.2–2.5 and 1.5–1.7 million. units/ha of germinating seeds for white mustard, 2.7–3.0 and 1.5–1.7 million units/ha of germinating seeds for oil radish and 2.0–2.2 and 1.2–1.4 million units/ha of germinating seeds for spring rape. After sowing, the seeds were rolled. The process of soil green manure production corresponded to the same period for all types of green manure plants – budding and flowering by preliminary disking. The final incorporation of the green manure into the soil was carried out by plowing to a depth of 25–27 cm to ensure optimization of the agricultural requirements for growing corn for grain.

The determination of agrophysical parameters of the soil, such as total porosity, capillary porosity, aeration porosity, and density of compaction, was carried out in accordance with standardized methods. These parameters were determined in the field where the green manure was produced with the onset of physical maturity of the soil in spring. The herbological situation on the field was assessed by quantitative weight and structural and species methods in accordance with generally accepted methods. In the process of setting up experiments and their general methodological support, the peculiarities of conducting research with cruciferous crops were taken into account. Statistical processing of the research results was carried out in accordance with standard statistical methods using a package of appropriate computer programs.

Assessment of hydrothermal conditions of the growing season of the studied green manure crops (August-October) showed some differences during the relevant period of research, which affected the intensity of growth processes of different green manure crops and determined the direction of their influence on the formation of corn yield. It should be noted that in accordance with the biological characteristics of green manure crops, the conditions of the research period (July 2018-October 2018 and similarly July 2019-October 2019) can be attributed to moderately favorable from the point of view of ensuring the appropriate growth processes and the formation of an appropriate level of leaf mass. At the same time, the conditions of the fall of 2018 were more favorable for the growth and development of green manure plants in all respects than the conditions of 2019. Thus, for the conditions of the experimental field of VNAU, the vegetation period of green manure (Figures 3.19–3.20) in 2018 was characterized by the amount of precipitation of 273.4 mm at an average daily temperature of 16.6 ◦C and a value of GTC of 1.34. The same parameters for the green manure growing season in 2019 were 161.7 mm, 16.2 ◦C and 0.81, respectively.

The climatic parameters of the green manure growing season for the conditions of the Uladovo-Lyulynetska breeding and research station were similar in terms of both the average daily temperature and the amount of precipitation and amounted to 265.5 mm, 16.5 ◦C, 1.31 for the period of 2018, and 116 mm, 16.4 ◦C and 0.65 for the period of 2019, respectively. This nature of the differences affected the peculiarities of growth processes and the amount of green manure mass of green manure plants in comparison of the two research sites and allowed to further evaluate the role of the factor of climatic parameters in the efficiency of their use among the species group of cruciferous crops.

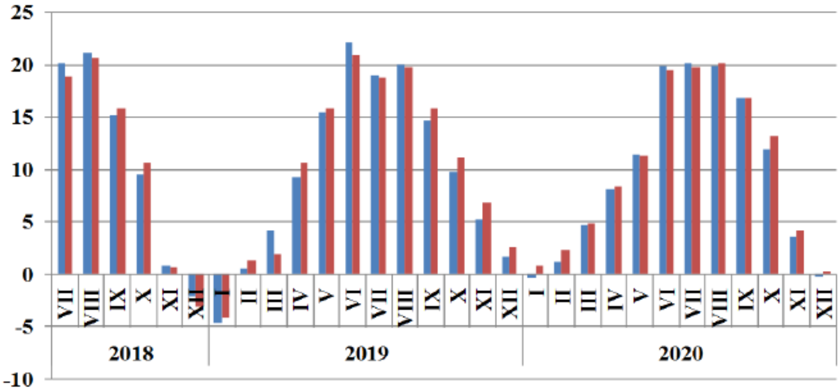


Figure. 3.19 – Average daily temperature over the study period, ◦C. (Blue color – Uladovo-Lyulynets DS, red color – VNAU Experimental Field) (based on the results of the author's own research)

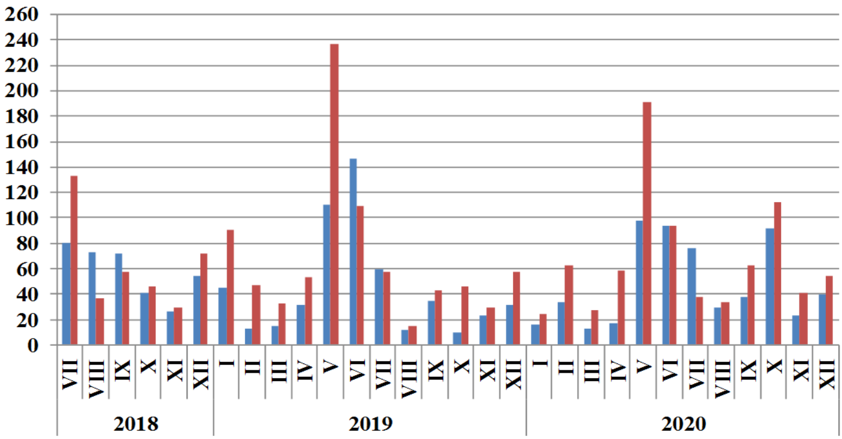


Figure 3.20 – Amount of precipitation over the study period, mm (blue – Uladovo-Lyulynets SSS, red – VNAU Experimental Field) (based on the results of the author's own research)

The obtained results of the research showed a significant difference in the effect of different types of green manure plants on the basic indicators of soil physical properties – porosity and density in the context of the studied layers of the arable horizon (0–30 cm) (Table 3.77) before the start of the main technological operations for growing corn for grain.

The use of all types of green manure plants contributed to the overall increase in both the total void space, including its subcategories, and the aeration void space. At the same time, this feature of the formation of porosity was noted both for chernozem soils in the conditions of the Uladovo–Lyulynets breeding and research station and for gray forest soils in the conditions of the experimental field of VNAU. This ultimately contributed to a decrease in soil density compared to the control variants. The most positive impact on this nature of changes was noted on average over the period of research in the variant of post–harvest green manure using oil radish, the use of which provided in the variant of conventional row sowing of green manure on chernozem soils an increase in total porosity in the soil layer of 0–30 cm by 8.4%, capillary – by 9.8%, non–capillary – by 6.5%, aeration porosity – by 13.1%. For the variant of wide–row sowing, these indicators were significantly lower and amounted to 3.5%, 3.9%, 2.8% and 6.0%, respectively.

On gray forest soils, the effectiveness of the formative effect in the trend of growth of indicators of agrophysical properties of the soil with the use of green manure was significantly higher. At the same time, as in the previous variant, the use of oil radish as a green manure had.

Thus, with row sowing, an increase in total porosity in the soil layer of 0–30 cm was observed by 12.5%, capillary porosity – by 11.9%, non–capillary porosity – by 13.3%, and aeration porosity – by 13.3%. With wide–row sowing, the corresponding range of indicators is almost two times lower. Compared to the variant of green manure with oil radish, the variant of green manure with white mustard on chernozem soils provided an increase in the total porosity by 5, 4 % (row sowing) and 1.7 % (wide–row sowing), capillary porosity – 7.2 % and 2.3 %, respectively, non–capillary porosity – 2.8 % and 0.9 %, respectively, aeration porosity – 11.3 % and 4.3 %, respectively.

Table 3.77

Soil porosity and density averaged at the stage of physical maturity of the soil before the start of mechanized operations for corn depending on the green manure variant (average for 2019-2020) (based on the results of the author's own research)

Porosity	Depth, cm	Control	White mustard		Oilseed radish		Rocket-cress		**LSD 05
			R*	W*	R*	W*	R*	W*	
1	2	3	4	5	6	7	8	9	10
In the conditions of the Uladovo-Lyulynets breeding and research station (deep low-humus black soil)									
Total	0-10	53.0	56.3	53.8	58.1	55.3	53.6	53.3	1.33
	10-20	52.8	55.3	53.9	57.1	54.5	53.8	53.2	1.18
	20-30	50.5	53.2	51.4	54.3	51.8	51.5	50.9	0.84
	0-30	52.1	54.9	53.0	56.5	53.9	53.0	52.5	1.08
Capillary	0-10	30.3	32.9	30.9	33.9	31.8	30.6	30.4	0.79
	10-20	31.5	33.1	32.3	34.2	32.7	32.1	31.7	0.64
	20-30	30.1	32.4	30.7	32.8	30.9	30.6	30.3	0.41
	0-30	30.6	32.8	31.3	33.6	31.8	31.1	30.8	0.67
Non-capillary	0-10	22.7	23.4	22.9	24.2	23.5	23.0	22.9	0.82
	10-20	21.3	22.2	21.6	22.9	21.8	21.7	21.5	0.61
	20-30	20.4	20.8	20.7	21.5	20.9	20.9	20.6	0.59
	0-30	21.5	22.1	21.7	22.9	22.1	21.9	21.7	0.74
Aeration	0-10	33.3	35.8	34.2	38.6	36.1	34.1	33.8	1.45
	10-20	30.6	33.9	32.1	34.9	32.1	31.5	30.9	1.47
	20-30	26.3	30.7	27.8	28.8	27.5	27.2	26.8	1.09
	0-30	30.1	33.5	31.4	34.1	31.9	30.9	30.5	1.39
Density, g cm^{-3}	0-10	1.30	1.23	1.28	1.20	1.25	1.28	1.29	0.05
	10-20	1.37	1.29	1.33	1.26	1.30	1.33	1.35	0.06
	20-30	1.40	1.34	1.36	1.31	1.36	1.36	1.38	0.05
	0-30	1.36	1.29	1.32	1.26	1.30	1.32	1.34	0.05
In the conditions of the VNAU experimental field (gray forest soils)									
Total	0-10	42.7	47.7	45	49.3	46.1	44.6	43.7	1.41
	10-20	40.4	43.7	41.8	45.2	42.8	42.0	41.4	1.22
	20-30	38.9	41.6	39.8	42.8	40.6	40.5	39.5	0.92
	0-30	40.7	44.3	42.2	45.8	43.2	42.4	41.5	1.20
Capillary	0-10	23.3	26.5	25.1	27.2	25.5	24.5	23.9	0.83
	10-20	22.6	24.1	23.5	25.1	23.9	23.6	23.2	0.71
	20-30	22.2	23.2	22.7	23.9	23.1	22.9	22.5	0.49
	0-30	22.7	24.6	23.8	25.4	24.2	23.7	23.2	0.69

(End of Table 3.77)

1	2	3	4	5	6	7	8	9	10
Non-capillary	0-10	19.4	21.2	19.9	22.1	20.6	20.1	19.8	0.91
	10-20	17.8	19.6	18.3	20.1	18.9	18.4	18.2	0.75
	20-30	16.7	18.4	17.1	18.9	17.5	17.6	17	0.68
	0-30	18.0	19.7	18.4	20.4	19.0	18.7	18.3	0.80
Aeration	0-10	20.5	22.4	21.9	23.6	21.8	20.9	20.7	0.56
	10-20	17.6	18.5	17.9	19.4	18.7	18.3	17.8	0.47
	20-30	13.9	14.9	14.2	15.8	14.3	14.3	14	0.41
	0-30	17.3	18.6	18.0	19.6	18.3	17.8	17.5	0.45
Density, g cm^{-3}	0-10	1.40	1.34	1.35	1.30	1.36	1.39	1.37	0.03
	10-20	1.50	1.38	1.43	1.35	1.41	1.49	1.49	0.04
	20-30	1.57	1.50	1.54	1.46	1.50	1.53	1.55	0.05
	0-30	1.49	1.41	1.44	1.37	1.42	1.47	1.47	0.04

Notes. * R – row seeding option, W – wide-row seeding option; ** – for values in % after conversion to arctg.

On gray forest soils, these growth values were generally 28.2% (row sowing) and 59.8% (wide-row sowing) higher than on black soil. The lowest level of growth of indicators was noted in the variant of using spring rape as a green manure – the average increase in the types of porosity by 2.0% for row and 0.92% for wide-row sowing on chernozem soils, and by 3.84% and 1.75%, respectively, on gray forest soils. As a result, the dynamics of porosity formation had a positive effect on the value of soil density with the maximum value of soil density optimization in the variant of row sowing with oil radish on chernozem soils at 1.26 g/cm^3, and on gray forest soils with the same sowing variant at 1.37 g/cm^3, which is 7.4% and 8.1% lower, respectively, compared to the control. We explain the results obtained by the specifics of the development and formation of the root systems of the studied green manure plants. In the case of oil radish (Fig.), a thickened taproot system with deep penetration into the soil is formed during the summer sowing period.

At the appropriate planting density, this ensures intensive drainage of the root layer of the soil, and the presence of morphologies with intensive thickening and intensive skeletal branching ensures intensive skeletonization of the corresponding soil layer, which ultimately provides a change in the corresponding values of porosity and density. In addition, the intensive radial growth of the root system of oil radish provides intensive differentiation of the soil layer into capillary and non-capillary structures with an increase in the overall aeration porosity.

In contrast to oil radish, in white mustard, the formation of the root system is aimed at the development of a pronounced taproot, but it is characterized by the formation of pronounced horizontal branching, less thickness and lower penetration depth in the part of maximum thickening. As a result, we noted less pronounced drainage of the topsoil and its differentiation into structural aggregates. These differences are more clearly noted in other studies, the results of which on the study of the dynamics and features of the formation of root systems of white mustard and oil radish are presented in Figures 3.21–3.22.

For spring rape during summer sowing, the formation of the root system in comparison with oil radish and white mustard was noted as the least intensive: the least development and radial thickening at a lower depth of penetration. As a result, these features are reflected in the influence of the respective types of green manure on the formation of soil porosity and its density. At the same time, based on our research, it should be noted that the use of green manure on soils with less favorable agrophysical properties provides a more significant positive effect in their optimization.

Regarding the influence of the sowing method on these indicators, it should be noted that for all types of green manure under wide-row sowing, a general increase in the habitus of the root system with its thickening and branching was observed, while reducing the overall depth of its penetration. However, this general increase does not compensate for the differentiation of the soil layer into strips with green manure plants and interstrip space without them.As a result, the average value of radial and vertical drainage is lower than in the variant of the row seeding method.

This is confirmed by the values of indicators for all types of green manure in comparison of row and wide–row sowing methods.

Our studies also showed a positive effect of the use of all types of green manure on the formation of quantitative and weight and species forms of weeds in the field before plowing green manure. The significance of this effect in comparison to the control was determined by the type of green manure plant. Thus, in the conditions of the Uladovo–Lyulynetska experimental breeding station, the maximum reduction of total weediness was noted in the variant of post–harvest green manure with oil radish for row sowing for different locations of the research by 59.8–66.3%, for wide–row sowing – by 50.5%–55.4%, which in the values of weed mass was 62.9–67.0% and 31.2–50.6%, respectively. The herbicide–regulating role of white mustard at its close value was on average 10.2–15.3% lower compared to oil radish. A similar indicator for spring rape was almost twice lower compared to the same variant of oil radish.

Figure 3.21 – Root system of oil radish (upper left position), white mustard (upper right position), spring rape (lower left position) and possible morphotypes of the root system of oil radish (lower left position) (black square size 2x2 cm) (based on the results of the author's own research)

It should also be noted that the maximum effect of the use of all types of green manure on both chernozem and gray forest soils was observed for biological groups of wintering weeds (total reduction within the types of green manure 32.3–70.3% for row and 26.0–47.5% for wide–row sowing) and late spring weeds (54.7–74.2% and 50.3–65.4%, respectively).

This species specificity of green manure effect is due to the development cycle of specific biological groups of weeds and aspects of their abundance when cultivating green manure in the summer and autumn growing season.

Figure 3.22 – Dynamics of root system formation of white mustard (left position) and oil radish (right position) (1 – 72 days, 2 – 64 days; 3 – 59 days; 4 – 52 days after full germination) (Source: https://kursi–floristiki.ru/ovoshchi/redka–maslichnaya–kak–siderat.html). Source: based on our own research.

It is also worth noting the effect of green manure not only on the number of weeds, but also on their weight.In particular, in the variant with a larger number of weeds, their weight is lower than the same number in other variants.

In particular, such a disparity in weed weight reduction while maintaining their number should be noted in the variant of white mustard and oil radish, which is evidence of the general suppressive effect of these types of green manure not only at the stage of weed germination, but, importantly, at the stage of its active growth.

Again, the explanation for such peculiarities of the impact of different green manure on the level of weed infestation should be noted that for all green manure variants, weed control efficiency depended on the growth rate of the aboveground vegetative mass, the intensity of closing the total field coverage with the assimilation surface of green manure plants. In turn, the growth rate of vegetative green manure aboveground mass depended primarily on the moisture conditions that develop in the first two to three weeks after sowing green manure. For both years of research and their locations, hydrothermal conditions were moderately favorable for the formation of the corresponding leaf–stem mass. However, the variants of conventional row sowing were more productive in terms of both the intensity of mass formation and herbological control of oil radish plants in relation to weeds of the post–harvest or post–mowing cycle of development (Fig. 3.23).

Thus, in the comparison of the row and wide-row variants of siderate formation, the intensity of exposure coverage of the surface of the accounting plots with siderate before the beginning of the stemming phase was on average 18.4–33.7% (depending on the year of observation) higher in the variant of conventional row sowing. The structure of the leaf-stem mass also varied. Thus, in the phase of the beginning of stemming in the version of the usual row sowing of oil radish, the share of the stem accounted for 25.6–30.9% and the share of leaves – 69.1–74.4%. For white mustard and spring mustard, these indicators were 32.6–40.2 and 59.8–67.4% and 35.1–46.3 and 53.7–64.9%, respectively. For the variant of wide-row sowing, this ratio in oil radish had a different character: 39.5–44.9 and 55.1–60.5%, respectively. For white mustard under wide-row sowing, the stem share was 2.8–5.2% less than for oil radish. In the version of the spring suripitia, the share of the stem increased by 2.8–4.5%. At the same time, we noted significant differences in the intensity of the rate of development of siderates. Thus, among the initial stages before the rosette phase, white mustard showed more intensive growth rates than oil radish and spring horseradish. However, starting from the stemming phase, oil radish plants show more intense growth rates, which, taking into account the greater biological adaptability of oil radish itself to low temperatures, are maintained until the period of siderate plowing. For the variant of spring sorghum with a lower level of autumn adaptation, the intensity of the growth of leaf-stem mass had the lowest rates and, accordingly, the format of its use by the factor of reducing field weediness had the lowest overall effect. These conclusions are clearly confirmed by the preliminary data analysis (Table 3.78).

Table 3.78

Number and mass of weeds before plowing post-harvest siderates, average for 2018–2020 (based on the results of the author's own research)

Варіант сидерації		Number of weeds, pcs. m^{-2}					Mass of weeds, g m^{-2}				
		Biological group of weeds				In total	Biological group of weeds				In total
		vigorous early	vigorous late	overwintering	perennial		vigorous early	vigorous late	overwintering	perennial	
In the conditions of the Uladovo-Lyulynetsk breeding and research station											
Without siderate (control)		9.6	10.2	2.3	1.5	23.6	72.3	65.3	18.9	9.8	166.3
Post-harvest siderate of oilseed radish	R*	3.2	2.1	0.6	0.7	6.6	20.6	24.5	7.7	2.1	54,9
	W*	4.2	3.3	1.2	1.0	9.7	56.2	41.8	12.3	4.2	114,5
Post-harvest siderate of white mustard	R	4.4	3.5	0.9	0.9	9.7	28.9	35.0	12.4	3.6	79,9
	W	5.2	4.1	1.3	1.2	11.8	32.9	41.6	17.8	5.3	97,6
Post-harvest siderate of rocket-cress	R	7.2	5.1	1.9	1.3	15.5	61.8	50.9	16.0	8.1	136,8
	W	7.9	5.6	2.0	1.3	16.8	65.3	54.8	16.9	8.7	145,7
LSD_{05}		1.4	0.9	1.1	0.3	0.9	10.8	11.3	8.1	1.5	24.1
In the conditions of the experimental field of VNAU											
Without siderate (control))		14.8	15.5	3.6	2.6	36.5	95.2	93.0	35.6	12.2	236.0
Post-harvest siderate of oilseed radish	R*	5.6	4.8	1.2	1.1	12.7	30.9	40.5	12.8	3.4	87,6
	W*	6.9	5.7	1.9	1.6	14.1	46.4	50.5	14.9	4.9	116,7
Post-harvest siderate of white mustard	R	6.6	6.2	1.5	1.4	15.7	41.8	45.0	18.4	8.6	113,8
	W	8.4	7.7	1.8	1.9	19.8	47.9	49.3	20.1	9.8	127,1
Post-harvest siderate of rocket-cress	R	8.2	6.3	1.9	1.3	17.7	49.8	49.6	20.0	10.5	129,9
	W	8.8	6.9	2.2	1.6	19.5	51.2	52.6	20.9	11.3	136,0
LSD_{05}		1.1	0.8	1.0	0.5	1.2	11.4	11.5	8.5	1.9	25.3

Note: * R – row sowing option, W – wide row sowing variant

Source: based on own research.

It should also be noted that the hydrothermal conditions during the period from sowing to plowing of the siderate had a significant effect on the productivity of the siderate culture. As already noted, the conditions of 2018, both in terms of the amount of precipitation and the value of the hydrothermal coefficient, met certain requirements of weather models to ensure sideration, which positively affected the size of the leaf-stem mass of all without excluding siderate plants. However, it should be noted that the level of adaptability of siderats (according to the difference in the yield of leaf stem mass in the optimal and less favorable year) was maximum in the option of applying oil radish, especially in the option of row sowing, ensuring the level of productivity on average for the years and places of research by 11 .6% higher than in white mustard and by 49.6% higher than in the case of spring mustard. A positive influence of the potential of soil fertility on the formation of leaf-stem mass of siderates was also established. So, on black soil soils, the yield of oil radish was 3.9 t ha^{-1} higher than on gray forest soils. And for white mustard and spring mustard, this difference was 3.2 and 2.7 t ha^{-1}, respectively. This emphasizes the edaphic features of oil radish noted in a number of publications.

The results of the study of the aftereffect of sider crops on the amount of weediness of corn on the grain under which the actual version of siderization is carried out (Table 3.79) showed a decrease in general and specific weediness at the 8–10 leaf phase. At the same time, it was established that the level of reduction of the total number of weeds averaged for the research sites was 50.1% for the row sowing variant and 40.0% for the wide-row sowing during the period of the research using oil radish as a post-harvest siderate. For the sideration option using white mustard and spring mustard – 48.6 and 39.5% and 30.6 and 23.7%, respectively. Under these conditions of overall efficiency, the maximum reduction in the number of weeds was noted for spring early group, perennial and winter weeds. In our opinion, this nature of the formation of indicators is consistent with the previously made conclusions regarding the level of weediness during the plowing period of siderate and the specifics of the influence of siderate in the process of mineralization of the leaf-stem mass of cruciferous siderates from the point of view of their influence on the germination and viability of the seeds of perennial and spring cycle weeds development The obtained positive effect on the agrophysical properties of the soil, the improvement of the phytosanitary condition of the field, and the applied leaf-stem mass as an alternative to organic fertilization contributed to an increase in the yield of corn per grain in our experiment (Table 3.79). It should be noted that the period of 2019–2020 for the formation of the yield of corn hybrids in Vinnytsia was difficult, especially the conditions of 2020 with a long abnormally cold period in the first period of its vegetation up to the 810 leaf phase.Due to these reasons, the level of corn yield per grain for both study sites had significant differences in accounting for the harvest of 2019 and 2020. The average yield of corn grain did not exceed 7.4 t ha^{-1} in the conditions of the Uladovo-Lyulynetsk selection and research station and 6.2 t ha^{-1} in the conditions of the VNAU experimental field on gray forest soils. The averaged results of the yield value for different sideration options show its positive influence on the formation of corn grain yield.

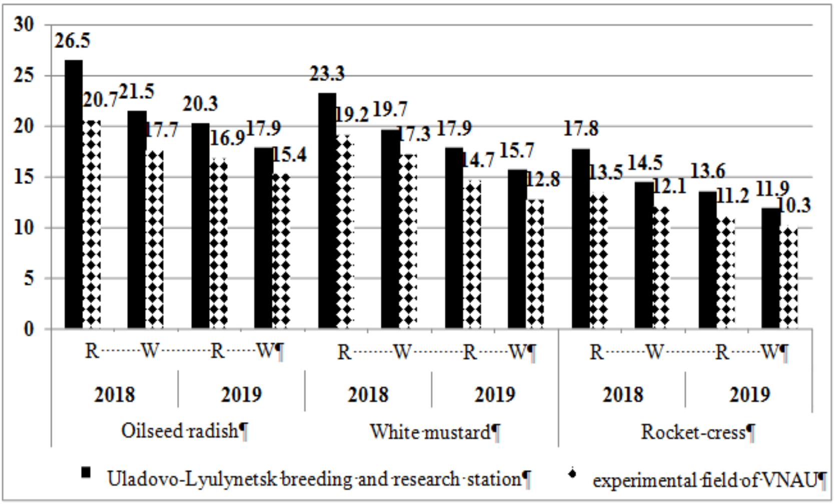


Figure 3.23 – Leaf-stem mass of siderates before plowing, t/ha, 2018–2019 (P – row sowing variant, Ш – wide-row sowing variant; LSD_{05} (t ha^{-1}) for the comparison group 1.14)

Source: formed on the basis of own research (based on the results of the author's own research)

Table 3.79

Distribution of biological groups of weeds in corn crops for grain under different sideration options for the 8-10 leaf phase (hybrid SI Respect (FAO 240)), average for 2018-2020 (based on the results of the author's own research)

Option of sideration		Biological group of weeds												In total	
		vigorous early			vigorous late			over-wintering			perennial				
		pcs. m^{-2}	% to all	g m^{-2}	pcs. m^{-2}	% to all	g m^{-2}	pcs. m^{-2}	% to all	g m^{-2}	pcs. m^{-2}	% to all	g m^{-2}	pcs.m^{-2}	g m^{-2}
In the conditions of the Uladovo-Lyulynetsk breeding and research station															
Without siderate (control)		20.6	43.9	216	18.5	39.4	211	3.9	8.3	49.9	3.9	8.3	50.0	46.9	526.9
Oiseed radish	R*	11.4	52.8	154	8.6	39.8	159	0.9	4.2	19.8	0.7	3.2	19.6	21.6	352,4
	W*	13.5	51.3	171	10.2	38.8	178	1.4	5.3	28.4	1.2	4.6	25.6	26.3	403,0
White mustard	R	13.9	52.1	183	10.8	40.4	168	1.1	4.1	26.3	0.9	3.4	23.8	26.7	401,1
	W	15.2	49.8	196	12.4	40.7	175	1.6	5.2	31.5	1.3	4.3	30.9	30.5	433,4
Rocket-cress	R	16.5	48.4	209	13.3	39.0	180	2.2	6.5	37.3	2.1	6.2	33.4	34.1	459,7
	W	17.2	46.2	212	14.8	39.8	189	2.7	7.3	41.8	2.5	6.7	41.5	37.2	484,3
LSD_{05}		1.5	–	21.7	1.9	–	33.6	0.6	–	15.8	0.5	–	12.5	1.4	21.0
In the conditions of the experimental field of VNAU															
Without siderate (control)		27.8	43.8	254	25.8	40.6	292	4.3	6.8	67.8	5.6	8.8	62.8	63.5	676.6
Oiseed radish	R	16.3	47.8	169	13.5	39.6	185	2.2	6.5	29.7	2.1	6.2	25.7	34.1	409,4
	W	18.2	44.8	179	16.9	41.6	192	2.8	6.9	32.5	2.7	6.7	37.4	40.6	440,9
White mustard	R	14.5	49.8	168	9.4	32.3	183	2.8	9.6	36.3	2.4	8.2	37.8	29.1	425,1
	W	18.1	50.8	184	11.2	31.5	225	3.1	8.7	45.6	3.2	9.0	42.3	35.6	496,9
Rocket-cress	R	18.5	44.0	216	17.3	41.2	223	3.5	8.3	54.1	2.7	6.4	46.3	42.0	539,4
	W	20.2	43.4	224	18.6	40.0	242	3.9	8.4	60.3	3.8	8.2	50.4	46.5	576,7
LSD_{05}		1.9	–	25.3	1.9	–	36.9	0.7	–	19.8	0.5	–	14.2	1.6	24.2

Note. * R – row sowing variant, W – wide row sowing variant

Source: formed on the basis of own research

The maximum yield increases for both the row and wide row seeding options were noted for the use of oil radish with an increase compared to the control without sideration for row sowing of 0.77 t $ha^{-1}$for growing corn on chernozem soils and 0.80 t $ha^{-1}$for growing on gray forest soils. In the variant of wide-row seeding, the yield indicators of corn were 19–27% lower compared to the row variant of sowing siderate. The yield of corn under other variants of siderates was on average 4.5% less than using white mustard and 7.7% less than using spring mustard. Smaller values of increments compared to the values of optimization of agrophysical parameters of the soil and the level of weediness indicate that there are aspects of the mechanistic action of sideral crops on the formation of yield and the actual chemistry of the transformation of leaf-stem mass in soils and its agronomic value from the standpoint of chemical composition, the content of macro- and microelements and other derivatives, which affect both chemical reactions in the soil-absorption complex, as well as the availability of plants and their physiological growth processes.Thus, we established that the use of sideration with cruciferous plant species is an effective means of regulating the agrophysical properties of the soil, controlling segetal vegetation and biologizing soil nutrition. Such an accumulative technological effect ensures the growth of agricultural productivity. crops and corn in particular, at least in the range from 0.3 to 0.8 t ha^{-1}.

Among the cruciferous siderates, it is worth noting the oilseed radish, which, possessing the already noted high adaptive potential and a guaranteed high level of leaf-stem mass formation, relatively undemanding to soil fertility conditions, provides significant advantages in the format of post-harvest sideration providing all existing advantages of cruciferous sideral cultures. Taking into account the data obtained by us, oil radish should be recommended as a component of biologized systems of alternative fertilization of agricultural crops for the conditions of the Pravoberezhny Forest Steppe in the option of row sowing with a sowing rate of 2.7–3.0 million pieces/ha of similar seeds immediately after the collection of the predecessor, provided the appropriate minimum level of soil moisture reserves.

The perspective of further research is to study the features of the processes of mineralization of the leaf-stem mass of oil radish and aspects of the influence of this process on the agrochemical properties of the soil, humus accumulation, soil microbiota and other related processes. Clarification also requires the study of cruciferous siderates for combined use with straw and its own species combination.

Table 3.80

Corn grain yield depending on sideration options, average for 2019-2020, t ha^{-1} (hybrid SY Respect (FAO 240), A is a factor of year conditions) (based on the results of the author's own research)

Option of sowing post-harvest siderate (B)	Variant of the siderata plant (C)			
	Control	White mustard	Oilseed radish	Rocket-cress
In the conditions of the Uladovo-Lyulynetsk breeding and research station				
Normal string (R)	7.41	7.87	8.18	7.66
Wide-row (W)		7.69	8.03	7.44
LSD05, t/ha (for the interaction of ABC factors before control)		0.15		
In the conditions of the experimental field of VNAU				
Normal string (R)	6.18	6.64	6.98	6.42
Wide-row (W)		6.47	6.78	6.29
LSD05, t/ha (for the interaction of ABC factors before control)		0.18		

Source: formed on the basis of own research

The effectiveness of oil radish in the option of post-harvest sideration has been proven (Gudz et al., 2011). Experimental studies were carried out in 2006–2009 in a stationary field experiment based on the scientific and practical center of the Sumy National University, which is part of the Myrhorod-Sum agro-soil district of the left-bank part of the Forest Steppe of Ukraine. The scheme of the field experiment included the following variants of the main tillage:

1. Shelf plowing to a depth of 28–30 cm (control).
2. Shelf-less processing to a depth of 28-30 cm (with a combined KLD-3.0 unit).
3. Shallow tillage to a depth of 13-15 cm (BDT-3 disk harrow).
4. Shelfless processing to a depth of 6-8 cm (combined unit AG-2,4).

The effectiveness of the main tillage methods was studied on two backgrounds: – siderable (follow-up sowing of oil radish) and siderless (returning post-harvest and root residues of winter wheat to the soil).

The use of post-harvest siderate, as well as the main tillage, directly affected the density of the soil under potato crops. Thus, against the background of siderate, the volumetric mass of the arable layer of the soil decreased significantly – on average by 0.04 g/cm^3 during both tillage and plowing (Table 3.81).

Table 3.81

The influence of the methods of main cultivation and sideral background on the volume mass in the 0-30 centimeter soil layer during potato cultivation, g cm^{-3} (average for 2006–2009) (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of basic soil cultivation (factor B)				Average for factor A	+, -
	Organic fertilizers (factor A)	Police-less to a depth of 28-30 cm	Shelfless to a depth of 13–15 cm	Shelfless to a depth of 6-8 cm		
Without green manure	1.20	1.18	1.21	1.21	1.20	-
Post-harvest siderate	1.15	1.13	1.17	1.18	1.16	-0.04
Average factor B	1.17	1.16	1.19	1.20		
Difference	-	-0.018	0.014	0.024		

$LSDR_{05}$ total = 0.017. factor A = 0.009. factor B = 0.012

A greater reserve of productive moisture in the arable soil layer in potato crops was facilitated by the incorporation of siderate into the soil, compared to the wrapping of only root and stubble residues of winter wheat (Table 3.82).

During the period of growing potatoes, the reserves of productive moisture of a meter-long soil layer decreased by 28–29 mm, depending on the studied factors (Table 3.83).

Among the studied factors, the use of post-harvest siderate had the greatest influence on the tuber yield, the share of which was 15.3%.

In order to ensure better conditions of soil density, water consumption of potato crops and the formation of high yields, it is advisable to carry out deep tillage without the main tillage with the earning of post-harvest siderates of oil radish.

The comprehensive integrated indicator of the research was the determination of the yield of potato tubers (Table 3.84).

Table 3.82

The influence of the methods of main cultivation and siderate on the reserves of productive moisture in the 0-30-centimeter soil layer during potato cultivation, mm (average for 2006–2009) (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of basic soil cultivation (factor B)				Average for factor A	+, -
	Organic fertilizers (factor A)	Police-less to a depth of 28-30 cm	Shelfless to a depth of 13–15 cm	Shelfless to a depth of 6-8 cm		
Without green manure	30.4	32.2	31.7	32.5	31.7	-
Post-harvest siderate	32.7	34.7	33.4	34.8	33.9	2.2
Average factor B	31.6	33.4	32.5	33.6		
Difference	-	1.9	1.0	2.1		
LSD_{05} total = 1.02, factor A = 0.51					Factor B = 0.72	

Application of post-harvest green manure, compared to non-sideral background, significantly increased potato yield on all variants of soil tillage methods – by 3.96.2 t ha^{-1}. On a non-sidereal background, inhibitory zone of falling line showing response of the yield to average daily temperature during potato vegetation period is clearly evident after 19^{0}C. On the background of covering oil radish siderate, negative impact of increase in average daily temperatures appears out of optimum zone of 20–21^{0}C. This regularity proves that application of green fertilizer increases stress resistance of the crops to negative impact of average daily air temperatures during vegetation period, which explains higher yield of the crop.

On the background with green manure application, the highest yield of potato was received with smaller amount of precipitation during its flowering, as optimal zone of yield response curve was within 110–130 mm of precipitation.

Table 3.83

Moisture consumption and water consumption coefficient of potato crops (average for 2006-2009) (Hudz et al., 2011)

Variant		Productive moisture reserves in the 0-100 centimeter soil layer, mm		Precipitation during the growing period, mm	Total water consum-ption, mm ha-1	Coefficient of water consumption
		at the time of planting	at the time of harvesting			
Deep plowing 28–30 cm	Without green manure	87.2	58.0	255.5	284.8	10.4
	Post-harvest siderate	91.1	61.6		285.1	8.9
Shelfless depth processing 28–30 cm	Without green manure	90.4	61.5		284.4	10.4
	Post-harvest siderate	94.0	65.4		284.0	8.3
Shelfless depth processing 13–15 cm	Without green manure	88.7	59.3		284.9	11.4
	Post-harvest siderate	92.0	62.5		285.0	9.5
	Without green manure	91.3	61.5		285.3	11.9
Shelfless depth processing 6–8 cm	Post-harvest siderate	94.8	64.9		285.4	10.1

According to results of another research (Mischenko et al., 2024), the variant with application of oilseed radish siderate and its covering by the method of tillage without ploughing to the depth of 28–30 cm provided the highest yield of potato – 30.3 t ha^{-1} (Figure 3.24).

Table 3.84

The effect of siderate and main cultivation methods on potato yield, t ha^{-1} (average for 2006–2009) (Hudz et al., 2011)

Organic fertilizers (factor A)	Methods of basic soil cultivation (factor B)				Average for factor A	+, -
	Organic fertilizers (factor A)	Police-less to a depth of 28-30 cm	Shelfless to a depth of 13–15 cm	Shelfless to a depth of 6-8 cm		
Without green manure	27.3	27.3	25.0	24.0	25.9	-
Post-harvest siderate	32.1	34.3	30.0	28.3	31.2	5.3
Average factor B	29.7	30.8	27.5	26.2		
Difference	-	1.1	-2.2	-3.5		
LSD_{05} total = 1.04		Factor A = 0.52			Factor B =	0.73

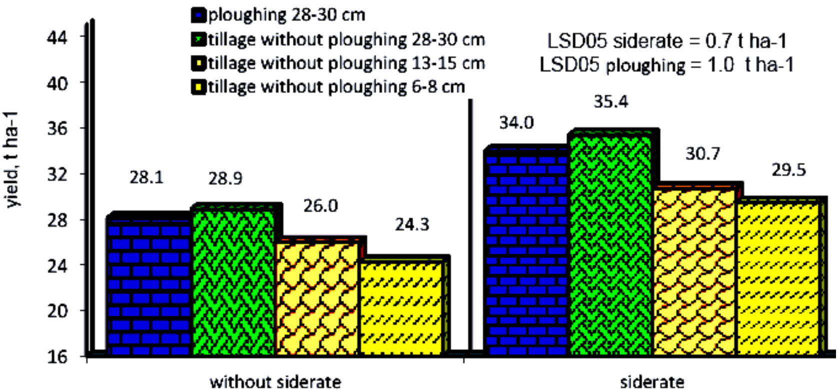


Figure 3.24 – Influence of siderate and main soil tillage on potato yield, t ha^{-1} (Mischenko et al., 2024)

The largest collection of starch was obtained with application of green manure – oil radish under tillage without ploughing in a depth of 28–30 cm – 4.03 t ha^{-1}, which was 0.3 t ha^{-1} more than under ploughing (Table 3.85).

Starch content in potato tubers ranged from 12.7 to 13.2%, it was significantly lower (by 0.4%) comparing with the control, with application of mineral fertilizer $N_{125}P_{63}K_{150}$. With organic fertilization, increase in starch content in tubers was greater than the control without siderate by 0.1%, largely due to green fertilizer of buckwheat.

Starch collection in all fertilization backgrounds was significantly higher than in the control without siderate, except for buckwheat siderate. The share of fertilizer influence on starch collection was 52%, year weather conditions – 42%, and other factors – 6%.

So, application of sideral background and deep tillage without ploughing contributed to formation of potato tuber yield with the best quality.

Table 3.85

Influence of basic tillage method and sideral background on technological indices of potato (Mischenko et al., 2024)

Background	Basic soil tillage			
	Ploughing 28–30 cm	Without ploughing 28–30 cm	Without ploughing 13–15 cm	Without ploughing 6–8 cm
starch content, %				
Without siderate	12.9	13.1	13.2	13.2
Siderate	13.1	13.3	13.4	13.5
starch collection, t ha^{-1}				
Without siderate	3.11	3.16	2.94	2.81
Siderate	3.73	4.03	3.56	3.40

Application of post-harvest siderate of oil radish and its covering by tillage without ploughing to a depth of 28–30 cm on typical black soil contributes to obtaining higher and better potato yields under conditions of unstable moisture in the North-Eastern Forest-Steppe of Ukraine.

When growing potato on the background of post-harvest oil radish siderate and with soil tillage without ploughing, lack of precipitation and high average daily temperatures had smaller effect on limiting yield level of the crop.

Based on yield data of our research, were calculated indices of economic attractiveness of potato growing. In general, green fertilizer of oil radish significantly increased potato value – by 18-25% for all methods of soil tillage comparing with background without siderate, Among the methods of covering oil radish, the highest value of potato – 3475.6 € ha^{-1} was obtained for non-ploughing tillage to a depth of 28–30 cm (Table 3.86).

Table 3.86

Technological indices of potato quality for different fertilization backgrounds (Mischenko et al., 2024)

Technological indices	Variant						LSD$_{05}$
	Without siderate (control	postharvest siderate				$N_{125}P_{63}K_{150}$	
		oilseed radish	phacelia	buckwheat	manure 25 t ha^{-1}		
Starch content, %	13.1	13.2	13.2	13.1	13.2	12.7	0.14
Starch collection, t ha^{-1}	3.25	4.08	3.87	3.37	3.92	3.71	0.25

Growing of post-harvest siderate of oil radish is a low-cost agricultural measure, and its covering by the method of tillage without ploughing provides saving of financial resources, comparing with ploughing. Covering of post-harvest oil radish siderate by tillage without ploughing to a depth of 28–30 cm, when growing potato, provided the lowest prime cost of potato tubers.

The effectiveness of oil radish as a siderate in the cultivation of pea crops has also been established. Thus, in the research of Muzika and Onychko (2016), it was noted that the highest yield of green mass of sideral plants in harvest crops (under the next year's vegetables) was obtained when sowing white mustard + oil radish (30.8 t/ha) against the background of the harvest residues of the predecessor + N_{10} for each ton of residues (Table 3.87). A slightly lower yield (29.6, 23.9 and 22.6 t ha^{-1}) was obtained when sowing oil radish, white mustard and spring rape against this background.

The highest content of nitrogen in terms of dry matter was noted in the seed mass of vetch (3.69%), peas (3.42%) and winter rape (2.99%). The content of other nutrients in the section of sideral plants was more stable. The supply of nutrients to the soil with the green mass of siderates depended on both their yield and the relative content of certain nutrients based on their dry matter. The highest nitrogen values were obtained on the plots of white mustard + oil radish, oil radish, peas and white mustard (respectively 105.6; 102.0; 92.1; 84.4 1 kg ha^{-1}). In terms of the total phosphorus content (P_2O_5), the best were – oil radish, white mustard +

oilseed radish, white mustard and wild rapeseed (35.5, 30.9 and 26.2 and 26.2 kg ha^{-}1, respectively).

The content of potassium in the crop of green mass of sideral plants exceeded the content of phosphorus by 1.5–3.7 times and was in the range of 65.5–156.7 kg ha^{-1}. According to this indicator, sideral plants are the best: oleaginous radish, white mustard + oleaginous radish and white mustard (the content of green mass in the harvest is 156.7¬124.5 1 kg ha^{-1}). Thus, the highest total content of nutrients in the harvest of the green mass of siderates in the autumn of 2010–2012 was obtained when growing against the background of harvest residues (+N10 per 1 t of residues) oil radish, joint sowing of white mustard and oil radish and white mustard, the plowing of green mass of which provided 294.2–235.1 kg ha^{-1} of NPK.

Table 3.87

Agrochemical characteristics and yield of siderates in harvest crops (sowing at the beginning of August, plowing at the end of the second to the beginning of the third decade of October) (Muzyka and Onychko, 2016)

№	Green manure	Yield, t ha^{-1}		Nutrient content, % on dry matter				The content of nutrients in the yield of siderat from 1 ha, kg CaO			
		raw mass	Dry mass	N	P_2O_5	K_2O	CaO	N	P_2O_5	K_2O	
Harvest residues of winter wheat + Nio for each ton of residues											
1.	White mustard	23.9	3.797	2.22	0.69	3.28	2.36	84.4	26.2	124.5	89.7
2.	White mustard + oilseed radish	30.8	4.150	2.54	0.74	3.26	2.45	105.6	30.9	135.2	101.7
3.	Sowing vetch	13.8	1.893	3.69	0.92	3.46	2.03	69.8	17.4	65.5	38.5
4.	Buckwheat	14.8	2.500	2.36	0.87	2.74	2.32	59.1	21.7	68.6	58.1
5.	Pea	17.8	2.693	3.42	0.73	2.86	1.96	92.1	19.8	77.1	52.7
6.	Winter rape	20.5	2.540	2.99	0.87	3.02	2.20	75.9	22.2	76.8	55.8
7.	Rape	22.6	3.057	2.63	0.86	3.40	2.28	80.4	26.2	104.0	69.8
8.	Oilseed radish	29.6	3.873	2.63	0.92	4.05	2.26	102.0	35.5	156.7	87.7

Calcium content in sidereal fertilizer is important for improving soil structure and reducing acidity. The content of CaO in the harvest of various sideral plants in the harvest crops of 2010-2012 was in the range of 101.7–38.5 kg ha^{-1}. In terms of the total amount of nutrients in the harvest of the green mass of sideral plants from one hectare in the autumn of 2010-2012, the best were the harvest crops of sideral plants: oil radish (381.9 kg ha^{-1}); white mustard + oilseed radish (373.4 kg ha^{-1}); white mustard (324.8 kg ha^{-1}); spring rapeseed (280.4 kg ha^{-1}).

Sowing sidereal plants on the harvest residues of the predecessor + N10 for each ton of residues with subsequent placement of them on the background of onion from seeds had a positive effect on the growth and development of plants (Table 3.88).

Table 3.88

Influence of green manure plants in stubble crops on biometric parameters of onion plants in the phase of 4–5 leaves, average 2011-2013. (Muzyka and Onychko, 2016)

№ п/п	Green manure	Фаза 4–5 листків					
		number of leaves, pcs..	total length of leaves, cm	average length of one leaf, cm	weight, g		
					plant	leaves	bulbs
1.	Control (no fertilizer)	4.6	109.7	23.8	9.6	6.1	3.5
2.	$N_{60}P_{60}K_{60}$	5.6	145.0	25.9	13.0	8.3	4.8
3.	White mustard	5.1	119.4	23.3	10.3	6.4	3.9
4.	White mustard + oilseed radish	5.3	125.9	23.8	11.0	7.0	4.0
5.	Sowing vetch	5.0	118.1	23.5	9.9	6.2	3.7
6.	Buckwheat	4.7	106.1	22.7	8.9	5.5	3.4
7.	Pea diaper	4.8	113.0	23.7	9.7	5.6	3.7
8.	Winter rape	4.9	118.0	23.9	9.7	6.0	3.7
9.	Spring rape	5.0	120.1	24.2	10.0	6.2	3.8
10.	Oilseed radish	5.0	126.3	25.1	10.8	5.6	4.2

Thus, the formation of the fifth leaf and bulbs against the background of sideral fertilization occurred 2–6 days earlier than plants from plots without fertilization. During the period of bulb formation, the best growth and development of onion plants was noted when placing its crops against the background of the harvest sowing of sideral plants: oil radish, white mustard + oilseed radish, spring rape, diaper pea – the total length of leaves of one plant is 279; 274; 266 and 264 cm, respectively, against 204 cm in plants of the control variant (without fertilizer). The weight of the plants of these variants was 114–107 g and the bulbs 31.9–30 g against 73 and 23 g in the control variant (increase of 56.246.6 and 38.7–30.5 %) (Table 3.89).

Table 3.89

Influence of green manure plants in stubble crops as the main fertilizer on biometric parameters of onion plants in the phase of bulb formation, average 2011-2013 (Muzyka and Onychko, 2016)

№	Green manure plants	Bulb formation phase					
		number of leaves, pcs.	total length of leaves, cm	average length of one leaf, cm	mass, g		
					plant	leaves	bulbs
1.	Control (no fertilizer)	6.05	203.5	33.6	73.0	50.0	23.0
2.	$N_{60}P_{60}K_{60}$	7.1	282.0	39.7	103.0	74.0	29.0
3.	White mustard	7.1	262.1	36.9	101.3	72.4	28.9
4.	White mustard + oilseed radish	7.3	273.9	37.5	112.0	80.5	31.5
5.	Sowing vetch	7.0	263.5	37.6	107.0	77.0	30.0
6.	Buckwheat	6.6	238.6	36.2	96.3	69.1	27.2
7.	Pea diaper	7.0	264.1	37.7	107.3	77.3	30.0
8.	Winter rape	6.9	260.2	37.7	104.0	74.4	29.6
9.	Spring rape	7.2	265.5	36.9	107.7	76.2	31.5
10.	Oilseed radish	7.3	279.0	38.2	114.3	82.4	31.9

Thus, when growing onions from seeds against the background of crop residues of the predecessor (root + straw) + N_{60} + green manure, oil radish should be used as a green manure plant, and oil radish + white mustard, spring rape should be grown together. In this case, the yield of onions is 20.4–19.6 t ha^{-1}.

The effectiveness of oil radish use in the system of typical models of organic crop rotation was also investigated. Thus, Khalep and Moskalenko (2020) developed basic (typical) models of organic crop rotations for crop farms in Polissya of Ukraine:

– Model 1: 1. Clover for seeds. 2. Winter rye + lupine (post-harvest for green manure). 3. Millet + oil radish (post-harvest for green manure). 4. Potatoes + winter rye (after harvesting potatoes for green manure). 5. Spring wheat with clover.

– Model 2: 1. Clover for seed. 2. Winter wheat + radish (after harvesting for green manure). 3. Soybeans + winter rye (post-harvest for green manure). 4. Buckwheat + oil radish (post-harvest for green manure). 5. Spring barley with clover.

– Model 3: 1. Clover for seeds. 2. Winter rye + radish (post-harvest for green manure). 3. Corn for grain + winter rye (after harvesting corn for green manure). 4. Peas. 5. Winter wheat + radish (after harvesting for green manure). 6. Oats with clover sowing.

– Model 4: 1. Clover for seeds. 2. Winter rye + lupine (post-harvest for green manure). 3. Millet + oil radish (post-harvest for green manure). 4. Peas. 5. Winter wheat + radish (post-harvest for green manure). 6. Potatoes + winter rye (after harvesting potatoes for green manure). 7. Spring wheat with clover.

In the above crop rotation schemes, along with their saturation with legumes and the cultivation of perennial grasses (clover), it is proposed to widely use green manure crops in the intermediate (after harvesting the main crops) periods – after all the main crops of the rotation (except for clover and winter crops predecessors), and not only after early cereals, as is now generally accepted. It should be emphasized that the natural and climatic conditions of Polissya (first of all, increased moisture availability compared to other natural and climatic zones and, in general, sufficient for the growth, development and accumulation of the necessary biomass of green manure sown in the intermediate (after harvesting the main crops) period, the length of the growing season after harvesting the main crops) fully allow for this approach.

The fertilizer potential and the share of green manure shown in the table will be formed in the process of crop rotation development and (after all the fertilizer system components are included in the fertilizer cycle and the projected crop yields with the corresponding by-product yields are achieved) will eventually reach stable values. This is confirmed by the graphical representation of the alignment of the series of dynamics of the actual values of the share of green manure in the total supply of nutrients from all sources according to the developed crop rotations.

The contribution of green manure to the processes of preserving and reproducing humus in the soils of organic agrocenoses is also important. According to the above-mentioned model calculations, the supply (preservation) of humus from the humification of biomass of different types of green manure is 0.11–0.25 t ha^{-1} per year (depending on the timing of sowing and the corresponding biomass yield). At the same time, their share in the total volume of humus formation is 6.4–27.2% in the fields of various main crops, where we offer them for cultivation in intermediate crops. On the basis of 1 hectare of crop rotation area, the contribution of green manure to the processes of humus formation is 0.09–0.13 tons or 4.7–6.4% of the share according to the models (Table 3.90).

At the same time, out of several tested statistical analysis functions, the polynomial function of the sixth degree was chosen, the results of which demonstrated the highest closeness of connection (R^2) – from 0.9898 for model №. 3 to 0.9942 for model № 1.

Table 3.90

Forecast of the supply of basic nutrient compounds for modeled crop rotations (in accessible form for an average year after crop rotation development) (Khalep and Moskalenko, 2020)

Indicators	Model № 1			Model № 2			Model № 3			Model № 4		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
From all sources per 1 ha of crop rotation area, kg	106	44	108	101	42	89	109	45	108	106	45	104
including green manure, kg ha^{-1}	25	9	20	19	8	24	23	9	26	26	10	23
Share of green manure, %.	23.6	20.5	18.5	18.8	19.0	27.0	21.2	20.5	24.0	24.5	22.2	22.1

Based on the comparison of the data in Table 3.91 and Table 3.92, we conclude that the contribution of green manure to the formation of potential soil fertility (share in the volume of humus formation) of the considered models is less significant than the contribution to the formation of effective fertility (share in the volume of supply of basic nutrients). At the same time, it should be emphasized that it is thanks to green manure biomass as an additional source of humus supply (preservation) that positive humus balances are achieved in a number of cases, in particular, in models 2 and 4. Along with the above-mentioned great general importance of using green manure crops in the intermediate (after harvesting the main crops) periods for green fertilization in organic farming, attention should be paid to the features and factors of their selection for inclusion in crop rotation schemes. Legumes, especially lupine, are considered to be the best green manure crops in terms of NPK (especially nitrogen) content and other biologically beneficial traits. We have calculated the supply of nutrients with green manure biomass per hectare of sown area in terms of the main green manure crops (Table 3.91).

Table 3.91

Forecast of organic matter (humus) supply to agrocenoses of the developed crop rotation models (on average for a year after crop rotation development) (Khalep and Moskalenko, 2020)

Indicators	Model № 1	Model № 2	Model № 3	Model № 4
Total amount of newly formed (preserved) humus per 1 ha of crop rotation area, t	2.10	1.85	2.13	2.02
including from humification of green manure biomass, t ha^{-1}	0.10	0.09	0.10	0.13
Share of green manure, %.	4.8	5.1	4.7	6.4

The authors of this study (Khalep and Moskalenko, 2020) concluded that green manure, including sowing green manure crops in the intermediate (after harvesting the main crops) period, is the most versatile, balanced, publicly available, relatively easy to reproduce and manageable reserve for increasing productivity, in particular of organic agrocenoses. For organic crop production farms, in the absence of the possibility of using such an important source of fertilizer as manure, sowing green manure crops in the intermediate (after harvesting the main crops) period is an important factor in increasing the fertilizing potential of crop rotations. This is especially true for the agrocenoses of Polissya with their relatively low–fertility soils.

Table 3.92

Calculation of nutrient compound yields for the main green manure cropscrops (by gross content) (Khalep and Moskalenko, 2020)

Green manure	Biomass accumu-lation, t ha^{-1}	Content in 1 ton of biomass, kg (after Berdnikov et al., 2012)			Output per 1 ha, kg			
		N	P2O5	K2O	N	P2O5	K2O	NPK
Narrow-leaved lupine	24.0	4.1	1.1	2.3	98.4	26.4	55.2	180.0
Lupine perennial	20.0	4.8	0.9	3.0	96.0	18.0	60.0	174.0
Seradella	18.0	4.5	1.3	3.5	81.0	23.4	63.0	167.4
White sweet clover	15.0	6.5	0.7	2.1	97.5	10.5	31.5	139.5
Diaper	15.0	4.7	1.3	4.2	70.5	19.5	63.0	153.0
Phacelia	12.0	3.6	1.2	4.4	43.2	14.4	52.8	110.4
Winter rye	20.0	3.2	1.1	2.7	64.0	22.0	54.0	140.0
White mustard	10.0	3.7	1.2	4.0	37.0	12.0	40.0	89.0
Winter rape	13.0	3.7	1.2	4.0	48.1	15.6	52.0	115.7
Perko	15.0	3.7	1.2	4.0	55.5	18.0	60.0	133.5
Oilseed radish	23.0	3.7	1.2	4.0	85.1	27.6	92.0	204.7
Annual ryegrass	21.0	3.8	1.2	2.8	79.8	25.2	58.8	163.4

The natural and climatic conditions of Polissya (first of all, increased moisture availability compared to other natural and climatic zones) are generally sufficient for the growth, development and accumulation of the necessary biomass of green manure crops sown in the intermediate (after harvesting the main crops).

It was found (Mishchenko, 2015) that on average in 2006–2010, when growing sugar beets, oil radish green manure, compared to the control without green manure, provided an increase in the content of hydrolyzed nitrogen in the 0–30 cm layer by 8–12% to 105–107 mg kg^{-1}, mobile phosphorus by 7–11% to 123125 mg kg^{-1} and potassium by 9–12% to 120–122 mg kg^{-1}under all soil treatments. Under potato crops, the advantage of green manure over the control is more pronounced, which resulted in a higher content of nitrogen –111–114 mg kg^{-1}, phosphorus – 127–130 mg kg^{-1}, and potassium – 121124 mg kg^{-1}against the background of green fertilizer.

The incorporation of oil radish green manure by deep moldboardless tillage at 28–30 cm provided the highest content of nutrients in the

0–30 cm soil layer. This method of incorporation of green fertilizer of oil radish provided significantly higher nutrient supply to the test crops and differed within the error range before moldboardless loosening to a depth of 13–15 cm under potatoes in terms of nitrogen content (where it was determined to be 113 mg kg^{-1}) and before plowing to 2830 cm in terms of phosphorus content (129 mg kg^{-1}). The highest localization of nutrients to the soil surface was determined when green manure was not plowed to a depth of 6–8 cm in the soil layer of 0–10 cm (Table 3.93).

Table 3.93

Content of nutrients in soil layers under test crops under different fertilization and tillage backgrounds, average for 2006-2010, mg/kg (Mishchenko, 2015)

Variant		hydrolyzed nitrogen | mobile phosphorus | mobile potassium								
fertilizer background	soil cultivation	soil layer, cm 0-10 1 10-20 1 20-30 1 0-10 1 10-20 | 20-30 | 0-10 | 10-20 | 20-30								
sugar beet										
without green manure (control)	plowing 28–30	105	98.3	88.4	125	117	103	117	110	101
	shelfless 28–30 cm	110	97.3	83.7	131	115	97.6	122	108	97,7
	shelfless 13–15 cm	113	94.1	80.5	135	111	94.1	125	105	94,5
	shelfless 6–8 cm	117	86.0	78.5	139	106	89.5	127	103	90,9
post-harvest green manure of oilseed radish	plowing 28–30	117	105	92.3	135	126	109	131	121	109
	shelfless 28–30 cm	126	105	89.7	143	124	107	139	120	107
	shelfless 13–15 cm	131	100	85.5	149	121	101	141	118	103
	shelfless 6–8 cm	136	96.5	82.2	154	116	98.1	143	116	100
LSD_{05} green manure		0,9	1.0	1.0	0.8	0.7	1.0	0.9	0.8	0.8
LSD_{05} processing		1,3	1.4	1.4	1.1	1.0	1.4	1.2	1.1	1.1
potato										
without green manure (control)	plowing 28–30	109	102	93.7	125	120	109	119	112	103
	shelfless 28–30 cm	113	100	88.4	129	118	105	121	109	101
	shelfless 13–15 cm	116	97.5	84.3	133	114	102	123	107	96.9
	shelfless 6–8 cm	119	93.3	81.5	136	110	99.0	124	104	92.7
post-harvest green manure of oilseed radish	plowing 28–30	122	111	98.8	139	131	115	131	124	111
	shelfless 28–30 cm	137	110	94.7	146	130	113	139	123	109
	shelfless 13–15 cm	142	108	88.6	150	127	107	140	120	105
	shelfless 6–8 cm	146	104	86.2	154	123	105	142	118	102
LSD_{05} green manure			1.3	1.2	1.2	0.9	0.7	1.0	0.7	1.2
LSD_{05} processing			1.8	1.7	1.7	1.3	1.1	1.5	1.0	1.7

On average, in 2006–2010, nitrogen 75.4 kg ha^{-1}, phosphorus 55.4 kg/ha and potassium 97 kg ha^{-1} were supplied to the soil on the background without green manure with by–products; on the background of oil radish green mass application, 211, 111 and 238 kg ha^{-1}of the same macronutrients were supplied, respectively.

According to the balance of nutrients, the agrochemical efficiency of methods of planting post–harvest residues and green manure is estimated (Table 3.94). The removal of nutrients by crops, as well as the value of their yield, was the highest for plowing and moldboardless tillage to a depth of 28–30 cm with the use of green fertilizer; the lowest removal rates were found for moldboardless loosening to a depth of 6–8 cm on a green manure–free background. When growing sugar beets, a higher nitrogen removal was obtained – by 23.931.8 kg ha^{-1}, and potatoes – phosphorus and potassium – by 4.4–11.5 and 17.159.6 kg ha^{-1}.

Under sugar beet in the control without green manure, the nitrogen balance was negative and under no–till cultivation to a depth of 6–8 cm it was minimal – 56.9 kg ha^{-1}. With deep moldboardless tillage at a depth of 28–30 cm, the nitrogen deficit increased to 74.8 kg ha^{-1}.

Against the background of green manure, a positive nitrogen balance was established, respectively, for the above treatments – 56.2 and 34.4 kg ha^{-1}. Similar patterns of nitrogen balance were determined under potatoes.

The phosphorus balance in the control without green manure under sugar beet varied within 8 kg ha^{-1}. With oil radish green manure, it increased by 7 times, and under potatoes, respectively, by 12 times, which is associated with a greater removal of phosphorus by the yield of potato tubers.

The potassium balance in the control without green manure under sugar beet was negative and amounted to 78 kg ha$^{–1}$under no–till tillage at 28–30 cm and plowing at the same depth, while under shallow tillage at 6–8 cm the potassium deficit decreased to 59 kg ha$^{–1}$. With the introduction of oil radish green manure, the potassium balance was positive and increased to 61–74 kg ha$^{–1}$with different tillage methods. Due to the intensive removal of potassium by the potato crop in the control without green manure, the deficit of this element in deep tillage was 98 kg ha$^{–1}$, and with the introduction of green manure it increased and did not exceed 34 kg ha$^{–1}$in no–till tillage to a depth of 6–8 cm.

Table 3.94

Nutrient balance under row crops with different fertilization and tillage backgrounds, average for 2006–2010 (Mishchenko, 2015)

Variant		Receipts, kg ha-1			Harvest yield, kg ha^{-1}			Balance, kg ha^{-1}			Intensity of the balance sheet, %		
fertilizer background 1 tillage		N 1 P_2O_5 1 K_2O			N1$P_2O_5$1K_2O			N 1 P_2O_5 1 K_2O			N1$P_2O_5$1K_2O		
sugar beet													
without green manure (control)	plowing 28–30 cm	75.4	55.4	97	150	49.5	175	- 74.3	5.9	-77.5	50.4	112	55.6
	shelfless 28–30 cm	75.4	55.4	97	150	49.7	175	-74.8	5.7	-77.7	50.2	112	55.5
	shelfless 13–15 cm	75.4	55.4	97	140	46.5	163	-65	8.9	-65.5	53.7	119	59.7
	shelfless 6–8 cm	75.4	55.4	97	132	43.7	156	-56.9	11.7	-58.6	57.0	127	62.3
post-harvest green manure of oilseed radish	plowing 28–30 cm	212	112	238	175	54.4	175	36.4	57.1	62.8	121	205	136
	shelfless 28–30 cm	212	112	238	177	54.9	177	34.4	56.6	60.8	119	203	134
	shelfless 13–15 cm	212	112	238	161	51.3	172	50.3	60.2	65.9	131	217	138
	shelfless 6–8 cm	212	112	238	155	49.8	164	56.2	61.7	74.3	136	224	145
potato													
without green manure (control)	plowing 28–30 cm	75.4	55.4	97	122	52.9	195	-46.8	2.5	-98	61.7	101	49.8
	shelfless 28–30 cm	75.4	55.4	97	122	53.0	195	-46.9	2.4	-98.1	61.7	101	49.7
	shelfless 13–15 cm	75.4	55.4	97	113	51.0	180	-37.7	4.4	-83.3	66.7	109	53.8
	shelfless 6–8 cm	75.4	55.4	97	108	49.0	173	-33.0	6.4	-75.7	69.5	113	56.2
post-harvest green manure of oilseed radish	plowing 28–30 cm	212	112	238	143	63.1	229	68.3	48.5	9.1	148	177	104
	shelfless 28–30 cm	212	112	238	152	66.4	237	59.8	45.1	1.3	139	168	101
	shelfless 13–15 cm	212	112	238	134	59.4	214	77.4	52.2	23.7	158	188	111
	shelfless 6–8 cm	212	112	238	127	56.7	203	84.3	54.8	34.6	166	197	117

The authors of the study (Mishchenko, 2015) concluded that in the conditions of the Left–Bank Forest–Steppe of Ukraine, post–harvest oil radish green manure formed phytomass – 29.1–29.7 t ha^{-1}, and accumulated nitrogen – 136.1–144.4.1 kg/ha, phosphorus – 51.7–56.1 kg ha^{-1}, potassium – 140.9–157.1 kg ha^{-1}and calcium – 174.6–178.3 kg ha^{-1}.

The use of oil radish green manure under sugar beet and potatoes contributed to an increase in the content of easily hydrolyzed nitrogen in the root layer of soil 0–30 cm by 9.813.8 mg kg^{-1}, mobile phosphorus by 8.0–13.8 mg kg^{-1}and exchangeable potassium by 7.8–13.0 mg kg^{-1}compared to the unfertilized background.

The planting of oil radish green manure by moldboardless tillage at a depth of 28–30 cm provided the highest content of easily hydrolyzed nitrogen – 106.7 and 113.8 mg kg^{-1}, mobile phosphorus – 124.6 and 129.6 mg kg^{-1}and exchangeable potassium – 121.7 and 123.6 mg kg^{-1} during the period of sugar beet and potato cultivation.

The phytomass of green manure had the greatest influence on the content of nitrogen in the root layer of soil 0–30 cm – 49–52%, and the least – on phosphorus – 24–25%. The content of nutrients was more dependent on the post–harvest green manure of oil radish – by 21.9–31.9% than on the main tillage – 0.3–1.3%. Green fertilizer of oil radish had a higher share of influence on the content of nutrients in plowing – 33–66% and moldboardless tillage with a depth of 28–30 cm – 19–61%.

The post–harvest green manure of oil radish provided a positive balance of nutrients for sugar beet and potatoes. The most positive balance of nutrients –34.6–84.3 kg ha^{-1} was on the background of green manure under moldboardless tillage by 6–8 cm; increasing the depth of moldboardless tillage to 28–30 cm brought the balance closer to a balanced one. The highest yield of sugar beet (35.4 t ha^{-1}) and potatoes (30.3 t/ha) was obtained with moldboardless incorporation of oil radish green manure to a depth of 28–30 cm; the difference to plowing was significant – by 1.4 and 1.8 t ha^{-1}, respectively, as well as to shallow moldboardless soil loosening – by 4.7 and 3.7 t ha^{-1}and surface loosening – by 5.9 and 5.1 t ha^{-1}.

It is noted (Shevchenko, 2021) that one of the important methods of biologization is the introduction of green manure pairs. The importance of green manure in modern agriculture is due to their participation in the reproduction of soil organic matter, which globally affects the entire range of agronomic properties of the soil. Humus and nitrogen reserves in agricultural soils are restored both through the application of mineral fertilizers and organic matter that enters the soil in the form of plant residues of various origins, in particular, as a result of plowing green manure from green manure crops. Its systematic plowing in the amount of 15–20 t/ha provides an effect that is equivalent to the application of 20 t ha^{-1}of manure.

The choice of green manure crops is an important priority in the issue of green manure in Ukraine. It is necessary for this crop to have a short growing season, to grow a large amount of vegetative mass, and to be economically profitable in terms of seed production. It is known that in the steppe zone, such crops as peas, spring vetch, white sweet clover, sainfoin, white mustard, spring and winter rape, buckwheat and oil radish can be grown for green manure.

For eight years, the Erastiv Research Station has been conducting research to determine the effectiveness of various legumes and cruciferous crops as green manure crops for the purpose of using their biomass as organic fertilizer. According to the results of the research, it was found that the most effective and appropriate for widespread implementation were sowings of oil radish either in pure form or in a mixture with spring vetch (Table 3.95).

Table 3.95

Comparison of green manure crops efficiency (Shevchenko et al., 2021)

Crops	Green mass		Root remains		Total dry matter yield, t ha^{-1}
	harvest, t ha^{-1}	dry matter content, %	harvest, t ha^{-1}	dry matter content, %	
White mustard	19.1	13.1	4.7	30	3.91
Spring vetch	22.1	18.2	4.9	33	5.64
White mustard + spring vetch	21.5	15.6	5.5	31	5.06
Oilseed radish + spring vetch	28.2	16.8	6.7	32	6.88

The effectiveness of green fertilizer largely depends on the size of the green manure crop. The more green mass is incorporated into the soil, the more noticeable will be its effect and aftereffect on the productivity of the following crops in the rotation.

The authors of the study emphasize (Shevchenko et al., 2021) that the analysis of oil radish plants showed that its green mass in terms of absolutely dry matter contained an average of 2.10% nitrogen, 1.54% phosphorus, and 3.88% potassium, and 1.47%, 0.97%, and 3.56% in the roots. When oil radish crops were harvested, 5.48 t ha^{-1} of organic matter was applied to the soil, which is equivalent to 29 t ha^{-1} of manure. Similar results are achieved by growing spring vetch, and the best results are achieved by growing them in a mixture.

So, the maximum yield of green manure in all years of research was formed when growing oil radish in a mixture with spring vetch, but the seed production of spring vetch and the use of its seeds in mixtures significantly increase the cost of green mass. Therefore, oil radish can be considered the most optimal crop for use as green manure in the northern Steppe.

The effectiveness of green manure application is confirmed by the experiments of the Erastiv Experimental Station: in fertilized crops, the yield of winter wheat on green manure under a favorable moisture regime is only 5–9% less than its yield on black manure, which is considered the most favorable predecessor for this crop. (But in unfavorable years, this difference can reach 20–25%).

A fairly thorough study was conducted by Sendetsky (2021). His research found that the destruction of straw and post–harvest residues with the biological product Vermistim–D, combined with sowing crops on green manure, led to an improvement in the agrophysical and agrochemical parameters of the soil.

According to the analysis of the structural composition of the soil, at the time of corn sowing, the number of clumpy (>10 mm) and small (<0.25 mm) fractions decreased by 2.53–2.3 and 0.4–0.8%, respectively, and the content of agronomically valuable aggregates (0.25–10 mm) increased by 2.0–3.2%, which led to a higher structural coefficient in these variants compared to the control by 0.09–0.21 and, respectively, by 0.10–0.17% at the time of harvest.

The total porosity of the 0–10 cm soil layer increased by 6.1–9.9%, and in the 10–20 cm soil layer – by 4.6–8.1%. The water resistance of structural aggregates of the 0–30 cm soil layer was higher by 5–9 relative % compared to the control. There was a positive trend of increasing the humus content by 0.06–0.15% compared to the control.

Table 3.96

Comparative characteristics of the fertilizer value of green manure crops (Shevchenko et al., 2021)

Crops	Dry matter added to the soil, t ha^{-1}	Amount of nutrients in total biomass, kg ha^{-1}				Litter equivalent, t
		N	P_2O_5	K_2O	total	
Oilseed radish	5.48	102	73	206	381	29
White mustard	3.91	71	37	91	199	15
Spring vetch	5.64	126	46	158	330	25
White mustard + spring vetch	5.06	103	46	130	279	21
Oilseed radish + spring vetch	6.88	141	75	226	442	34

The release of carbon dioxide (CO_2) increased compared to the control by 67 mgCO2/m^2 per day in the germination phase, by 144 mg CO_2 m^{-2} per day in the panicle ejection phase, and by 111 mg CO_2 m^{-2} per day in the waxy ripeness phase.

The studied agricultural measures on the use of straw and green manure in the cultivation of maize hybrids influenced the reduction of acidity of sod–podzolic soil, which in turn contributed to an increase in crop yield. A significant decrease in acidity (on average by 0.65 pH) occurred during the years of research in the variant of straw destruction "Vermistim–D" (6 l ha^{-1}) and sowing a mixture of white mustard and oil radish on green manure.

In all variants of the experiment, there was an improvement in field germination, plant density and plant survival until the harvesting period. The best results were observed in the variant of straw destruction and sowing a mixture of green manure (white mustard + oil radish): field germination of plants of the hybrid NC Lemero was 89.5%, NC Thermo – 88.9%, the number of plants after full germination, respectively, was 71360 and 71120 pcs. ha^{-1}, the number of plants before harvesting was 71075 and 70906 pcs. ha^{-1} (survival – 99.6 and 99.4%).

According to the results of the three–factor analysis of variance, the influence of the studied factors on the field germination of maize plants was 90.1%, of which: factor A (destruction) – 17.1%, factor B (green manure) – 59.6%, and factor C (maize hybrid) – 13.4% The rate of linear growth of plants was highest in the variant of straw and green manure with a mass of white mustard and oil radish. The average daily growth was 12 cm ahead of the growth of plants of the hybrid NK Termo and 16 cm ahead of the hybrid NK Lemero compared to the control.

It was found that when using straw and green manure, the assimilation surface of maize plants in the phase of panicle ejection was 6.12–5.71 thousand m^2 ha^{-1} higher, in the flowering phase – 4.20–3.10 thousand m^2 ha^{-1}, compared to the control. From the germination phase of maize plants to waxy ripeness, the photosynthetic potential of crops was higher than in the control by 0.614 million m^2day ha^{-1}.

Analysis of the structural elements of corn yield formation of the hybrid NK Termo showed that when straw was used in combination with green manure, on average over the years of research, the number of productive cobs per 100 plants was 1.0–1.7 pieces, the weight of the stem with leaves per plant was 20.7–52.2 g, the length of the cob was 0.7–1.6 cm and the weight of grain in one cob was 10.0–12.1 g higher compared to the control.

The weight of grain in the cob in the studied maize hybrids was influenced by certain factors: factor A (destruction of straw by Vermistim D) – 23.1%, factor B (green manure) – 48.0%, factor C (corn hybrids) – 6.4%, interaction of factors AB – 10.8%, interaction of other factors had no significant effect on the result The indicators of improvement of agrophysical and agrochemical, biological activity of the soil established in the variants of the experiment provided an increase in the yield of corn grain of hybrids NK Termo and NK Lemero (Table 3.97).

In all variants, the yield of corn grain of the hybrid Termo increased by an average of 7.0–37.4%, and of the hybrid Lemero by 8.1–36.0% compared to the control. The highest yield of NC Thermo – 11.7 t ha^{-1} (+ 3.2 t ha^{-1}), NC Lemero 11.6 t/ha (+ 3.0 t ha^{-1}) more compared to the control, was obtained in the variant of straw destruction in combination with sowing white mustard on green manure mixed with oil radish.

Corn grain yield was influenced by factors: A (straw destruction with Vermistim D) – 36.3%, B (green manure) – 38.9%, C (corn hybrid) – 6.6%, and the share of the influence of the interaction of factors A and B is 6%.

Studies have shown that the highest content of crude protein 9.7%, crude fat 5.12% and crude fiber 2.76% in the hybrid NK Termo was in the variant of straw destruction by Vermistim–D and sowing a mixture of white mustard and oil radish on green manure (increase in crude protein – 0.7%, crude fat – 0.76%, crude fiber – 0.36% compared to the control).

Table 3.97

Corn grain yield of NK Termo and NK Lemero hybrids using straw and siderate (average for 2013–2017), t ha^{-1} (Sendetskyi, 2021)

Variant	Year					Average for 5 years	± to control	
	2013	2014	2015	2016	2017		t ha^{-1}	%
hybrid NK Termo								
1	7.4	9.2	8.6	8.8	8.4	8.5	-	-
2	8.9	9.3	8.7	9.2	9.4	9.1	+0.6	7.0
3	9.3	10.8	10.1	10.8	10.3	10.3	+1.8	21.2
4	9.4	10.9	10.2	10.9	10.4	10.4	+1.9	22.3
5	9.5	11.1	10.3	11.0	10.5	10.5	+2.0	23.5
6	9.7	11.4	10.5	11.2	10.7	10.7	+2.2	25.9
7	10.2	11.7	10.8	11.5	11.6	11.2	+2.7	31.8
8	10.8	12.3	11.4	12.0	11.9	11.7	+3.2	37.4
hybrid NK Lemero								
1	7.8	9.4	8.9	8.8	8.1	8.6	-	-
2	9.1	9.5	8.9	9.4	9.6	9.3	+0.7	8.1
3	9.7	10.8	10.5	10.6	10.4	10.4	+1.8	20.9
4	9.8	10.9	10.6	10.8	10.5	10.5	+1.9	22.1
5	9.9	11.0	10.7	10.9	10.6	10.6	+2.0	23.3
6	10.2	11.2	10.9	11.2	10.8	10.9	+2.3	26.7
7	10.5	11.7	11.2	11.5	11.3	11.2	+2.6	30.2
8	11.0	12.1	11.6	12.0	11.7	11.6	+3.0	36.0
LSD_{05} A	-	-	-	-	-	*0.98*	-	-
LSD_{05} B	-	-	-	-	-	*0.49*	-	-
LSD_{05} C	-	-	-	-	-	*0.77*	-	-
LSD_{05} AB	-	-	-	-	-	*0.80*	-	-
LSD_{05} AC	-	-	-	-	-	*0.34*	-	-
LSD_{05} BC	-	-	-	-	-	*0.20*	-	-
LSD_{05} ABC	-	-	-	-	-	*0.06*	-	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

As a result of the calculations, straight–line regression dependencies of the resultant traits of crude protein content and crude fat content in corn grain of hybrids NK Termo and NK Lemero were established on the combined use of straw destruction with Vermistim D preparation with sowing of green manure in the technology of cultivation For both hybrids, optimal variants of the experiment were determined, which are characterized by the following linear equations: crude protein content – y 0.0475x + 8.89, R^2 = 0.8824; crude fat content – y = 0.0405x + 4.3248, R^2 = 0.8523. In both cases, a close correlation was established between the resultant and factor attributes, as evidenced by the high values of the determination coefficients.

The results of the research (Sendetskyi, 2021) on the study of the structural composition of the soil under corn sowing and the determination of the structural coefficient showed a fairly high structuring under the influence of the use of straw and green manure. In particular, at the time of sowing, the number of clumpy (>10 mm) and small (<0.25 mm) fractions decreased by 2.53–2.3 and 0.4–0.8%, respectively, and the content of agronomically valuable aggregates (0.25–10 mm) increased by 2.0–3.2%. This, in turn, led to a higher structural coefficient in these variants at the time of sowing compared to the control by 0.09–0.21 and, respectively, by 0.10–0.17% at the time of harvest (Table 3.98).

The highest indicators of the structural and aggregate composition of the soil were in the variant where the destruction of straw “Vermistim–D” 6 l ha^{-1} and sowing of crops on green manure (white mustard + oilseed radish) were performed. In this variant, the amount of aggregates in the 0–10 cm soil layer with a size of 0.25–10 mm at the time of sowing was 66.2%, or 6.1% more compared to the control with a structural coefficient of 1.72.

Our research has shown that the combined use of straw and green manure contributed to a decrease in soil density. In all variants of straw destruction with Vermistim–D in combination with green manure sowing, the density of the tilth (0–10 cm) layer was on average 0.08–0.10 g cm^{-3} less at the time of corn sowing and 0.10–0.12 g cm^{-3} at the time of corn harvesting compared to the control (Table 3.98).

Table 3.98

Structural and aggregate composition of tilthy soil under the use of straw and green manure of maize agrocenosis (average for 2013–2017) (Sendetskyi, 2021)

Variant	Share of units (%) by size						Structural coefficient	
	>10		10-0,25		<0,25			
	at the time of sowing	at the time of harvesting	at the time of sowing	at the time of harvesting	at the time of sowing	at the time of harvesting	at the time of sowing	at the time of harvesting
1	25.3	25.8	60.1	59.0	14.6	15.2	1.51	1.44
2	24.0	24.6	61.6	60.7	14.4	14.7	1.60	1.54
3	23.9	24.5	61.8	60.9	14.3	14.6	1.62	1.56
4	23.9	24.5	61.8	60.9	14.3	14.6	1.62	1.56
5	23.8	24.4	61.9	61.0	14.3	14.6	1.63	1.57
6	23.7	24.3	62.1	61.2	14.2	14.5	1.64	1.58
7	23.4	24.3	62.8	61.4	13.8	14.3	1.69	1.60
8	23.0	24.1	66.2	61.7	13.8	14.2	1.72	1.61

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Studies (Sendetskyi, 2021) have also shown that when straw and green manure were used compared to the control during sowing, the total porosity of the 0–10 cm soil layer increased by 8.4–9.9%, and the 10–20 cm layer by 6.1–8.1%, creating more favorable conditions for the growth and development of grain corn, better soil permeability as a basis for more productive use of precipitation (Table 3.100).

Soil moisture supply. Moisture is one of the most important factors in soil fertility, and its conservation and rational use largely depends on the impact of different farming systems. When straw destruction was carried out with Vermistim D in combination with sowing green manure, more favorable conditions were created for the growth and development of corn plants, better soil permeability as a basis for more productive use of precipitation (Table 3.101).

Table 3.99

Influence of straw and green manure on the density of sod-podzolic medium loam soil (average for 2013–2017), g cm^{-3} (Sendetskyi, 2021)

Variant	At the time of sowing		At the time of harvesting	
	soil layer, cm		soil layer, cm	
	0-10	10-20	0-10	10-20
1	1.26	1.27	1.32	1.35
2	1.23	1.24	1.27	1.30
3	1.22	1.22	1.26	1.28
4	1.20	1.21	1.25	1.27
5	1.19	1.20	1.24	1.26
6	1.18	1.19	1.22	1.24
7	1.17	1.18	1.21	1.23
8	1.16	1.18	1.20	1.23
LSD_{05} A	0.003	0.024	0.004	0.004
LSD_{05} B	0.002	0.016	0.003	0.003
LSD_{05} AB	0.002	0.008	0.001	0.001

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The accumulation of larger moisture reserves in the variants of combined use of straw and green manure compared to the control is explained by the overall improvement of the main agrophysical parameters of the soil, as well as the influence of straw and green manure as mulching material and organic matter, which reduce unproductive moisture loss from the soil.

Table 3.100

Influence of straw and green manure on the porosity of sod-podzolic soil (average for 2013–2017), % (Sendetskyi, 2021)

Variant	At the time of sowing		At the time of harvesting	
	soil layer, cm		soil layer, cm	
	0-10	10-20	0-10	10-20
1	50.3	51.2	48.2	48.0
2	56.4	55.8	53.4	52.8
3	56.8	56.2	55.1	55.1
4	56.9	56.4	55.5	55.4
5	57.6	56.8	56.3	56.7
6	58.7	57.3	57.8	57.1
7	59.1	58.6	59.0	58.1
8	60.2	59.3	59.4	59.6
LSD_{05} A	0.84	0.80	0.99	0.97
LSD_{05} B	0.48	0.37	0.57	0.54
LSD_{05} AB	0.27	0.19	0.24	0.30

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The level of soil structure in soils with heavy particle size distribution reflects not only natural fertility but also erosion resistance. Therefore, minimizing the physical degradation of soils is one of the conditions for increasing the environmental and economic efficiency of agricultural production. An important characteristic of soil macro-aggregates is their resistance to destruction, in particular under the influence of water. The water resistance of aggregates determines the quality of the soil structure and its agronomic value. Therefore, the study of the water resistance of soil aggregates under the influence of applied measures is important, since the physical condition of the soil and the conditions for plant development depend on their stability and stability. There is a close correlation between the amount of water-resistant aggregates >0.25 mm in size, on the one hand, and crop yields, humus reserves, soil density, soil moisture, and nutrient content, on the other. Increasing the number of water-resistant aggregates to 80% increases and extends the effect of these indicators.

It was found (Sendetskyi, 2021) that the use of straw in combination with green manure improved the water resistance of soil aggregates. Thus, in the variants of straw use in conjunction with green manure, the water resistance of structural aggregates of the 0–30 cm soil layer during the years of study was 5–9% higher compared to the control (Table 3.102).

Table 3.101

Moisture content of the tilth layer of soil (0-30 cm) under the use of straw in in combination with green manure (average for 2013-2017), % (Sendetskyi, 2021)

Variant	At the time of sowing corn	On average, when growing corn
1	19.8	19.1
2	20.4	19.5
3	20.5	19.7
4	20.5	19.7
5	20.7	19.9
6	20.9	20.1
7	21.2	20.6
8	21.4	20.8
LSD_{05} A	0.23	0.23
LSD_{05} B	0.06	0.05
LSD_{05} AB	0.02	0.02

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Studies have shown that in the maize field in all variants under different tillage methods, sowing the crop on green manure after incorporating straw into the soil increased the humus content in sod-podzolic soil.

Table 3.102

Effect of green manure on water resistance of soil structural aggregates in the layer 0–30 cm (average for 2013–2017), % (Sendetskyi, 2021)

Variant	At the time of sowing of corn		On average, during the growing season of corn	
	coefficient water resistance	% to control	coefficient water resistance	% to control
1	15.1	100	14.8	100
2	15.8	105	15.4	104
3	15.9	106	15.5	105
4	15.9	106	15.5	105
5	16.0	106	15.6	105
6	16.1	107	15.7	106
7	16.4	109	16.0	108
8	16.5	109	16.1	109
LSD_{05} A	*0.18*	-	*0.18*	-
LSD_{05} B	*0.05*	-	*0.05*	-
LSD_{05} AB	*0.02*	-	*0.02*	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The results of the research showed that the combined use of straw and green manure provided an average increase in the humus content in the tilth layer of soil by 0.09-0.15% in 2013-2018 compared to the control The largest increase in humus content (+ 0.15%) in sod-podzolic soil was in the variant with the combined use of straw and a mixture of green manure (white mustard + oil radish).

Studies (Sendetskyi, 2021) have shown that the combined use of straw and green manure in all variants of corn cultivation significantly reduced the acidity of sod-podzolic soils (Table 3.103).

Table 3.103

The impact of combined use of straw and green manure on the humus content in the tilth layer of soil (2013-2017), % (Sendetskyi, 2021)

Variant	Year					Average	± to control
	2013	2014	2015	2016	2017		
1	3.24	3.39	3.18	3.26	3.25	3.25	-
2	3.32	3.42	3.23	3.28	3.28	3.31	0.06
3	3.33	3.49	3.26	3.30	3.31	3.32	0.07
4	3.33	3.50	3.26	3.32	3.31	3.32	0.07
5	3.34	3.52	3.27	3.33	3.31	3.32	0.07
6	3.35	3.57	3.28	3.34	3.32	3.34	0.09
7	3.36	3.58	3.29	3.35	3.36	3.36	0.11
8	3.39	3.62	3.34	3.36	3.29	3.40	0.15
LSD_{05} A	-	-	-	-	-	*0.04*	-
LSD_{05} B	-	-	-	-	-	*0.01*	-
LSD_{05} AB	-	-	-	-	-	*0.003*	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Thus, on the basis of research during 2013–2017, it was found that in the variants where straw was destructed with Vermistim-D and incorporated into the soil and sown with white mustard and oil radish as green manure, the soil acidity was 0.39-0.65 pH lower than in the control (straw harvesting without destruction and sowing green manure).

A significant decrease in acidity (on average by 0.65 pH) occurred during the years of research in the variant of straw destruction with Vermistim-D (6 l ha^{-1}) and sowing a mixture of white mustard and oil radish for green manure.

The analysis of the study results showed that the combined use of straw and green manure influenced the dynamics of the respiration rate of sod-podzolic soil (Table 3.103). The biological activity of sod-podzolic soil in maize crops was different and depended on natural and climatic conditions, straw and green manure application, as well as on the time of its determination in different phases of growth and development of maize plants. Thus, in the variants where straw destruction was performed in combination with the green mass of white mustard and oilseed radish, the production of carbon dioxide by the soil increased during the growing season of the crop. When straw and a mixture of green manure (white mustard + oil radish) were applied, CO_2 emission in the maize agrocenosis increased by 66 mg CO_2 m^2 per day in the germination phase and by 144 mg CO_2 m^2 per day in the panicle ejection phase compared to the control.

Table 3.104

Effect of combined use of straw and green manure on the acidity of sod podzolic soil (average for 2013–2017), pH (Sendetskyi, 2021)

Variant	Year					Average	± to control
	2013	2014	2015	2016	2017		
1	4.8	5.2	4.9	5.0	5.1	5.03	-
2	4.9	5.5	5.2	5.1	5.3	5.22	+ 0.19
3	5.0	5.6	5.3	5.2	5.5	5.32	+0.29
4	5.0	5.6	5.3	5.2	5.5	5.32	+0.29
5	5.0	5.6	5.3	5.2	5.5	5.32	+0.29
6	5.1	5.7	5.4	5.3	5.6	5.42	+ 0.39
7	5.2	5.9	5.5	5.4	5.7	5.53	+ 0.50
8	5.3	6.1	5.7	5.6	5.8	5.68	+ 0.65
LSD_{05} A	-	-	-	-	-	*0.11*	-
LSD_{05} B	-	-	-	-	-	*0.03*	-
LSD_{05} AB	-	-	-	-	-	*0.009*	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Table 3.105

Intensity of carbon dioxide emission from sod-podzolic soil depending on the use of straw and green manure in agrocenosis corn (average for 2013-2017), mg CO_2 m^{-2} per day (Sendetskyi, 2021)

Variant	The phase of plant growth and development		
	seedlings	panicle ejection	wax ripeness
1	191	354	263
2	229	432	296
3	233	462	296
4	235	467	300
5	238	471	303
6	245	486	312
7	251	492	328
8	257	498	374
LSD_{05} A	1.28	2.06	1.37
LSD_{05} B	0.40	0.65	0.44
LSD_{05} AB	0.20	0.42	0.24

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The process of decomposition of organic matter begins with the hydrolysis of cellulose, which is a component of the cell membranes in plant residues. The resulting sugars are rapidly utilized by cellulosic bacteria and converted into other compounds.

Determination of the total biological activity by the degree of decomposition of flaxen fabric makes it possible to assess the intensity and characteristics of biological processes in the soil in the most general integrated form.

In the variants of straw and green manure application, the decomposition of flaxen fabric was more intense than in the control (Table 3.106).

Table 3.106

The effect of combined use of straw and green manure in corn agrocenosis on the decomposition of linen fabric in sod-podzolic soil (average for 2013–2017), % (Sendetskyi, 2021)

Variant	Observation period					
	phase 6-8 leaves			harvesting		
	horizon depth, cm					
	0-10	10-20	0-30	0-10	10-20	0-30
1	20.8	23.7	20.4	23.4	26.7	23.1
2	26.7	28.6	25.7	28.7	30.2	27.4
3	27.4	30.9	26.2	28.9	28.9	28.1
4	27.6	30.9	26.5	29.2	29.2	28.4
5	27.9	31.2	26.8	29.5	29.5	28.7
6	28.8	31.5	27.6	30.4	33.1	29.6
7	29.3	32.8	28.3	31.8	33.4	30.5
8	29.6	33.5	28.8	32.1	35.5	31.9

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

In the first half of the maize growing season, the dynamics of the intensity of flaxen fabric decomposition in the phase of 6–8 leaves was higher (by 8.8 relative %) in the soil layer of 0-10 cm, and 9.8 % in the soil layer of 10–20 cm in the variant of combined straw and green manure than in the control. This difference is leveled in the future. However, the decomposition of linen fabric in the variant of straw destruction "Vermistim-D" and a mixture of oil radish and white mustard was noticeably more active during the entire corn growing season.

The effect of using green manure is also manifested in a reduction in the level of weed infestation of crops and plant damage by pests and diseases that limit the growth of crop yields.

The aim of the research was to determine the effect of green manure on weed infestation of field crops in the Western Forest-Steppe. Our research on the impact of green manure on weeds in corn crops also showed their high efficiency (Table 3.107).

Table 3.107

Influence of destruction of residues of the predecessor and green manure on weed infestation of corn crops (average for 2013–2017) (Sendetskyi, 2021)

Variant	Number of weeds in the full germination phase			
	pcs. m^{-2}	± to control	dry weight, g m^{-2}	± to control
1	321	-	41.2	-
2	276	-45	36.3	-4.9
3	252	-69	32.4	-8.8
4	231	-90	31.9	-9.3
5	226	-95	29.6	-11.6
6	193	-128	24.6	-16.6
7	185	-136	20.5	-20.7
8	164	-157	18.7	-22.5
LSD_{05} A	4.12	-	2.29	-
LSD_{05} B	2.71	-	0.85	-
LSD_{05} AB	4.76	-	0.09	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

When counting the number of weeds in corn crops in the phase of full germination, it was found that in variants 4 and 5 the number of weeds was 185 and 164 pcs. m^{-2} , respectively, which is 136 and 157 pcs. m^{-2} less than in the control.

The best rate of weed reduction (51%) was observed in the variant of destruction with Vermistim-D, 6 l ha^{-1} with sowing a mixture of white mustard and oil radish on green manure. The physiological reaction of the most common weed species in the cenosis due to soil green manure was different. The stimulating effect of organic substances due to the humification of straw and green mass of oil radish was manifested in those weeds, the number of which did not decrease under the influence of green manure – common couch grass and creeping wheatgrass. The content of green pigment in the leaves of the tenacious marigold was stable and did not change.

The use of straw and green manure provided an increase in grain yield of maize hybrid Lemero by 8.1–36.0%. The highest yield on average over the years of research of 11.6 t ha^{-1} or 3.0 t ha^{-1} (36%) more than the control was in the variant where straw destruction was carried out with the preparation "Vermistim D" (6 l ha^{-1}) with simultaneous sowing of a mixture of white mustard and oilseed radish.

The results of the research showed that in all variants where straw destruction with Vermistim D (6 l ha^{-1}) in combination with green manure significantly improved the quality of corn grain of hybrids NK Termo and NK Lemero (Table 3.108).

Studies have established the highest content of crude protein 9.7%, crude fat 5.12% and crude fiber 2.76% in the hybrid NC Thermo in the variant of straw destruction by Vermistim-D and sowing a mixture of white mustard and oil radish on green manure (increase in crude protein – 0.7%, crude fat – 0.76%, crude fiber – 0.36% compared to the control).

In the hybrid NK Lemero on this variant, the content of crude protein was 9.6%, crude fat 4.92% and crude fiber 2.75% (an increase in crude protein – 0.9%, crude fat – 0.58%, crude fiber – 0.33% compared to the control).

The use of oil radish as a green manure for potato cultivation was effective (Molotskyi, 2005). The results of many research institutions and production practice show that the most promising for use as green manure crops are:

– crops suitable for intermediate cultivation;

– crops with a short growing season and high intensity of yield and biomass formation;

– crops that are undemanding to soil fertility elements, moisture and temperature;

– crops that do not require a large amount of fertilizers, protection products with the possibility of using a minimized method of soil cultivation;

– crops that do not reduce the productivity of subsequent crops and do not worsen the phytosanitary condition of the soil and crops.

Table 3.108

Grain yield of maize hybrids NK Termo and NK Lemero with the use of straw and green manure (average for 2013–2017), t ha^{-1} (Sendetskyi, 2021)

Variant	Year					Average	± to control	
	2013	2014	2015	2016	2017		t ha^{-1}	1 %
hybrid NK Thermo								
1	7.4	9.2	8.6	8.8	8.4	8.5	-	-
2	8.9	9.3	8.7	9.2	9.4	9.1	+0.6	7.0
3	9.3	10.8	10.1	10.8	10.3	10.3	+1.8	21.2
4	9.4	10.9	10.2	10.9	10.4	10.4	+1.9	22.3
5	9.5	11.1	10.3	11.0	10.5	10.5	+2.0	23.5
6	9.7	11.4	10.5	11.2	10.7	10.7	+2.2	25.9
7	10.2	11.7	10.8	11.5	11.6	11.2	+2.7	31.8
8	10.8	12.3	11.4	12.0	11.9	11.7	+3.2	37.4
hybrid NK Lemero								
1	7.8	9.4	8.9	8.8	8.1	8.6	-	-
2	9.1	9.5	8.9	9.4	9.6	9.3	+0.7	8.1
3	9.7	10.8	10.5	10.6	10.4	10.4	+1.8	20.9
4	9.8	10.9	10.6	10.8	10.5	10.5	+1.9	22.1
5	9.9	11.0	10.7	10.9	10.6	10.6	+2.0	23.3
6	10.2	11.2	10.9	11.2	10.8	10.9	+2.3	26.7
7	10.5	11.7	11.2	11.5	11.3	11.2	+2.6	30.2
8	11.0	12.1	11.6	12.0	11.7	11.6	+3.0	36.0
LSD_{05} A	-	-	-	-	-	*0.98*	-	-
LSD_{05} B	-	-	-	-	-	*0.49*	-	-
LSD_{05} C	-	-	-	-	-	*0.77*	-	-
LSD_{05} AB	-	-	-	-	-	*0.80*	-	-
LSD_{05} AC	-	-	-	-	-	*0.34*	-	-
LSD_{05} BC	-	-	-	-	-	*0.20*	-	-
LSD_{05} ABC	-	-	-	-	-	*0.06*	-	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

According to the requirements and a set of economically valuable traits, we selected green manure crops that meet the soil and climatic conditions of the zone, which were grouped into two blocks: spring oil radish, white mustard and their mixture and winter rye, winter rape and their mixture (Molotskyi, 2005).

Table 3.109

Corn grain quality indicators for the use of straw and green manure (average for 2013–2017), % (Sendetskyi, 2021)

Variant	Contained in an absolutely dry substance				
	Crude protein	**Crude fat**	**Crude fibre**	**Crude ash**	**Nitrogen-free extractives**
hybrid NK Thermo					
1	9.0	4.36	2.41	1.80	82.47
2	9.2	4.54	2.56	1.68	82.02
3	9.3	4.58	2.57	1.61	81.94
4	9.3	4.63	2.59	1.59	81.86
5	9.3	4.68	2.62	1.56	81.82
6	9.4	4.82	2.67	1.42	81.69
7	9.5	4.95	2.67	1.35	81.53
8	9.7	5.12	2.76	1.36	81.06
hybrid NK Lemero					
1	8.7	4.34	2.42	1.75	82.78
2	9.1	4.53	2.45	2.45	81.69
3	9.2	4.57	2.47	2.52	81.61
4	9.2	4.59	2.50	2.55	81.55
5	9.3	4.62	2.52	2.57	81.41
6	9.4	4.65	2.60	2.60	80.32
7	9.5	4.80	2.65	2.65	80.24
8	9.6	4.92	2.75	2.75	79.98
LSD_{05} A	*0.62*	*0.28*	-	-	-
LSD_{05} B	0.17	0.09	-	-	-
LSD_{05} C	*0.13*	*0.02*	-	-	-
LSD_{05} AB	*0.07*	*0.05*	-	-	-
LSD_{05} AC	*0.13*	*0.02*	-	-	-
LSD_{05} BC	*0.02*	*0.03*	-	-	-
LSD_{05} ABC	*0.04*	*0.03*	-	-	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Table 3.110

Experimental design (Molotsky, 2005)

Factor A	**Bearded pink (Ai)**		**Yavir (A2)**	
Factor B	Continuous cultivation (B i)	In crop rotation (B2)	Continuous cultivation (B i)	In crop rotation (B2)
Factor C.	- No fertilizer (C) - Manure 40 t ha^{-1} (C2) 3. Manure 40 t/ha + $N_{45}P_{45}K_{45}$ (C3) 4. $N_{45}P_{45}K_{45}$ (C4) 5. Oilseed radish (C5) 6. Oiseedl radish + $N_{45}P_{45}K_{45}$ 7. White mustard (C7) 8. White mustard + $N_{45}P_{45}K_{45}$) 9. White mustard + oil radish (C9) 10. White mustard + oilseed radish + $N_{45}P_{45}K_{45}$ 11. Winter rye 12. Winter rye + $N_{45}P_{45}K_{45}$ 13. Winter rape 14. Winter rape + $N_{45}P_{45}K_{45}$ 15. Winter rapeseed + winter rye 16. Winter rapeseed + winter rye + $N_{45}P_{45}K_{45}$			

It should be noted that in addition to the yield (roots + green mass) of green manure biomass, the content of basic nutrients in them is important, which depends on the growing conditions. It was found (Molotskyi, 2005) that on average over three years, green manure crops developed better and accumulated more nutrients when grown in a crop rotation compared to placement after potatoes, which were grown permanently (Table 3.111).

The biomass yield in permanent plantations and in crop rotation was dominated by spring green manure, where it averaged 213 and 262 c ha^{-1}, respectively, which is 35 and 44 c/ha more than in winter crops. However, winter crops prevailed in the accumulation of nutrients in the biomass of green manure.

If in a short-rotation crop rotation, when plowing biomass of spring crops, 77 kg/ha of nitrogen enters the soil, including 62 kg of green mass, 15 kg of roots; 21 kg of phosphorus, including 13 and 8 kg; 78 kg of potassium, including 60 and 18 kg; 1450 kg of carbon, including 868 and 590 kg, while using winter crops – 95 kg of nitrogen (69 and 26 kg); 26 kg of phosphorus (14 and 12 kg); 99 kg of potassium (76 and 23 kg); 1495 kg of carbon (792 and 709 kg), respectively.

With the constant cultivation of potatoes, the accumulation of nutrients in the biomass of green manure decreased, especially nitrogen, potassium and carbon. The phosphorus content remained almost unchanged.

The best green manure in terms of nutrient accumulation over an average of three years was a mixture of winter rye and winter rape, which was used to add 91–101 kg ha^{-1} of nitrogen, 26–28 kg of phosphorus, 88108 kg of potassium, and 1313–1544 kg ha^{-1} of carbon to the soil. However, it should be noted that pure winter rye was not inferior to the above variant in terms of nitrogen and phosphorus accumulation.

Table 3.111

Biomass yields of green manure crops and nutrient content, average for 2002–2004 (Molotskyi, 2005)

Variant	Continuous cultivation					In crop rotation				
	Harvest, c ha^{-1}	Content of the main elements nutrition, kg ha^{-1}				Harvest, c ha^{-1}	Content of the main elements nutrition, kg ha^{-1}			
		N	P_2O_5	K_2O	C		N	P_2O_5	K_2O	C
Oilseed radish	199	63	15	69	1141	250	66	15	77	1318
Oilseed radish*	215	66	18	80	1199	250	66	15	77	1318
White mustard	209	78	23	70	1284	273	89	26	76	1581
White mustard*	228	84	28	81	1367	273	89	26	76	1581
Oilseed radish + white mustard	204	73	20	70	1228	262	77	21	80	1450
Oilseed radish + white mustard*	225	80	24	82	1323	262	77	21	80	1450
Winter rye	165	97	26	67	1276	210	102	31	81	1497
Winter rye*	178	107	31	79	1346	210	102	31	81	1497
Winter rape	173	73	19	88	1225	221	83	19	108	1445
Winter rape*	187	79	22	100	1296	221	83	19	108	1445
Winter rye + winter rape	176	91	26	88	1313	224	101	28	108	1544
Winter rye + winter rapeseed*	189	98	30	101	1387	224	101	28	108	1544
Average for spring crops	213	74	21	76	1257	262	77	21	78	1450
Average for winter crops	178	91	26	87	1307	218	95	26	99	1495
Average for green manure	196	82	24	81	1282	240	86	23	88	1473
LSD_{05} (yield)=10,8 ц/га										

Notes. * – variants with subsequent application of mineral fertilizers ($N_{45}P_{45}K_{45}$)

Table 3.112

Yield of potato tubers depending on growing conditions, t ha^{-1}, average for 2002-2004 (Molotskyi, 2005)

Variant	Continuous cultivation		In crop rotation		Average by factor C	± to control		± to manure	
	variety Borodyanskaya pink	Variety Yavir	variety Borodyanskaya pink	Variety Yavir		c ha^{-1}	%	c ha^{-1}	%
No fertilizer (control)	177	199	209	228	2o3	-	-	-83	-29
40 tons of manure	252	271	304	315	286	83	41	-	-
40 t of manure + $N_{45}P_{45}K_{45}$	297	315	356	361	332	129	64	46	16
$N_{45}P_{45}K_{45}$	214	234	258	273	245	42	2o	-41	-14
Oilseed radish	205	225	248	266	236	33	16	-50	-17
Oilseed radish + $N_{45}P_{45}K_{45}$	239	258	289	303	272	69	34	-14	-5
White mustard	207	229	250	271	239	36	18	-47	-16
White mustard + $N_{45}P_{45}K_{45}$	243	262	293	307	276	73	36	-10	-3
Oilseed radish + white mustard	207	227	250	268	238	35	17	-48	-17
Radish + mustard + $N_{45}P_{45}K_{45}$	241	260	291	305	274	71	35	-12	-4
Winter rye	21o	232	254	273	242	39	19	-44	-15
Winter rye + $N_{45}P_{45}K_{45}$	251	271	302	317	285	82	40	-1	0
Winter rape	208	229	252	271	24o	37	18	-46	-16
Winter rape + $N_{45}P_{45}K_{45}$	251	268	302	315	284	81	4o	-2	-1
Winter rye + winter rape	212	234	256	275	244	41	2o	-42	-15
Winter rye + winter rape + $N_{45}P_{45}K_{45}$	254	273	307	319	288	85	42	2	1
Average by factor B	239		284						
Average by factor A	253	270	Factor (AB): F(1.192)=1.31; p<0.2540; LSD_{05}=5.57 c Factor (AC): F(15.192)=0.47; p<0.9527; LSD_{05}=15.74 c Factor (BC): F(15.192)=0.13; p<1.0000; LSD_{05}=15.74 c Factor (ABC):F(15.192)=0.05; p<1.0000; LSD_{05}=22.26 c						
Factor (A): F (1.192)=78.29; p<0.0000; LSD_{05}=3.93 c									
Factor (B): F (1.192)=502.21; p<0.0000; LSD_{05}=3.93 c									
Factor (C): (15.192)=73.42; p<0.0000; LSD_{05}=4.3 c									

Plowing of winter green manure crops (winter rye, winter rape and their mixture) increased the yield by 19, 18 and 20%, and the additional use of $N_{45}P_{45}K_{45}$ against the background of the listed green manure crops – by 40, 40 and 42%, respectively, compared to the variant where no fertilizers were applied.

Dobryva increased potato yields significantly. For the application of 40 t/ha of pus it increased by 41%, mineral dorivs ($N_{45}P_{45}K_{45}$) – by 20%, yarikh siderativs – by 16–18%, winter crops – by 1820%. At sodding of siderates with mineral fertilizers, the yield increased by 40–42%, which was equal to the indicators of the variant with the introduction of pus. Thus, siderates with low doses of mineral fertilizers are an alternative to pus.

According to the results of analysis of soil samples before sowing these crops, it was found that the presence of nematodes reached the level of 5–8 pcs l^{-1} of soil. After the grown sideral crops were used for green fertilizer, the number of nematodes in this volume of soil decreased by 1.7–4 times and was at the level of 1–3 pcs l^{-1} of soil. It was noted that when growing white mustard for green fertilizer, nematodes were not found in the soil. It should be concluded that in the process of plant growth and development, white mustard secretes mustard oils by its root system, which negatively affect the presence of nematodes in the soil (Table 3.113).

Table 3.113

Effect of green fertilization of sideral crops on the number of nematodes in the soil, pcs l^{-1}

Green manure crop	Prior to sowing sideral crops	After plowing of sideral crops		
		2021	2022	average
Without sidedress (control)	6–7	5	3	4
Pea-oat mixture 24.0 t ha^{-1}	5–6	4	2	3
Oilseed radish чная, 29,0 t ha^{-1}	6–8	3	1	2
White mustard, 30.6 t ha^{-1}	5–8	0	0	0
Narrow-leaved lupine, 26.0 t ha^{-1}	5–7	1	1	1

For 2021 and 2022 years of research, the average yield of cucumber fruits in the variant without fertilizers was 7.6 kg m^{-2} (Tables 3.114–3.115). Application of green fertilizer of sideral crops at the rate of 24.030.6 t ha^{-1}

against the background of mineral fertilizer dose N60P60K90 provided an increase in fruit yield at the level of 2.5-4.2 kg m^{-2}, or 32–55 % in relation to the control. The highest yield of cucumber fruits 11.8 kg m^{-2} and marketability of 88% was obtained with the use of sideral crop white mustard with its stocking on green fertilizer 30 t ha^{-1} + $N_{60}P_{60}K_{90}$.

The use of sideral crops as a green fertilizer on soils of protected ground allows saving mineral fertilizers in physical weight: nitrogen – 109.2–110.4 kg ha^{-1}, phosphorus respectively 31.2–42.8 and 96.2–127.6 kg ha^{-1} of potassium.

Studies on the effect of basic tillage on the productivity of beet cenosis were also carried out. No differences in yield were found between plowing and no-tillage loosening – 63.1 t ha^{-1} and 63.4 t ha^{-1}, and at zero tillage the yield of root crops decreased by 4.3 t ha^{-1} (6.8%). In variants with no-tillage loosening and plowing, sugar yield was 10.4–10.5 t ha^{-1} and was 0.7–0.8 t ha^{-1} (6.7–7.7%) higher than in the variant with zero tillage.

Table 3.114

Effect of green fertilization of sideral crops in cucumber cultivation in greenhouses, 2021–2022

Green manure crop	Yield, kg m^{-2}	Increment		Marketability, %
		kg m^{-2}	%	
Without sidedress (control)	7.6	-	-	74
Pea-oat mixture 24.0 t ha^{-1}	10.1	2.5	32	82
Oilseed radish чная, 29,0 t ha^{-1}	10.3	2.7	36	84
White mustard, 30.6 t ha^{-1}	11.8	4.2	55	88
Narrow-leaved lupine, 26.0 t ha^{-1}	11.4	3.8	50	86
LSD_{05}	0.48			

The influence of oilseed radish as a green manure in the assessment of carbon dioxide emissions (Sokolova et al., 2019). Field experiments were performed during 2015–2017. Experience variants: 1 – pure fallow (control), 2 – fallow with short-term sowing of oil radish. The studies were carried out in four-field (2 rotation) and five-field (1 rotation) crop rotations.

Table 3.115

Influence of technology elements on sugar beet productivity when sown in mulch

Variants	Yield, t ha^{-1}	Sugar content, %	Sugar yield, t ha^{-1}
Plowing (benchmark)			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	62.7	18.56	10.4
Cultivation with reverse compaction + ACSH	66.7	18.70	11.1
Direct seeding	59.9	18.68	9.9
Stubble (reference)	63.1	18.74	10.5
Straw	64.9	18.60	10.7
Oiseed radish	65.2	18.65	10.8
White mustard	61.5	18.50	10.1
Phacelia	60.9	18.74	10.2
Average	63.1	18.65	10.4
Tillage-free loosening			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	65.1	18.63	10.8
Cultivation with reverse compaction + ACS	66.6	18.71	11.0
Direct seeding	58.5	18.64	9.7
Stubble (reference)	61.9	18.64	10.2
Straw	64.6	18.63	10.6
Oiseed radish	65.1	18.67	10.7
White mustard	61.9	18.68	10.3
Phacelia	63.7	18.67	10.6
Average	63.4	18.66	10.5
Zero-treatment			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	57.2	18.49	9.5
Cultivation with reverse compaction + ACS	66.5	18.56	11.0
Direct seeding	52.7	18.26	8.6
Stubble (reference)	56.8	18.47	9.3
Straw	57.8	18.34	9.5
Oiseed radish	62.8	18.44	10.3
White mustard	59.6	18.42	9.8
Phacelia	57.1	18.51	9.4
Average	58.8	18.44	9.7
Average for pre-sowing treatment			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	61.7	18.56	10.2
Cultivation with reverse compaction + ACS	66.6	18.66	11.0
Direct seeding	57.0	18.52	9.4
Stubble (reference)	60.6	18.62	10.0
Straw	62.4	18.66	10.3
Oiseed radish	64.3	18.59	10.6
White mustard	61.0	18.53	10.1
Phacelia	60.6	18.64	10.1

Table 3.116

Productivity and technological qualities of sugar beet root crops

Variants	Mulch	Yield, t ha^{-1}	Sugar content, %	Sugar yield, t ha^{-1}
Plowing				
Pre-sowing cultivation with an AKSH	Stubble (reference)	61.4	18.65	10.2
	Straw	66.4	18.34	10.8
	Oiseed radish	64.8	18.65	10.7
	White mustard	61.5	18.37	10.1
	Phacelia	59.4	18.80	10.0
Cultivation with reverse compaction + ACSH	Stubble (reference)	66.1	18.93	11.0
	Straw	67.0	18.64	11.0
	Oiseed radish	69.0	18.70	11.5
	White mustard	65.1	18.51	10.7
	Phacelia	66.5	18.72	11.1
Direct seeding	Stubble (reference)	61.9	18.65	10.2
	Straw	61.2	18.82	10.2
	Oiseed radish	61.7	18.61	10.2
	White mustard	57.8	18.62	9.6
	Phacelia	56.7	18.69	9.4
Tillage-free loosening				
Pre-sowing cultivation with an AKSH	Stubble (reference)	62.0	18.53	10.2
	Straw	66.6	18.51	10.9
	Oiseed radish	67.3	18.72	11.2
	White mustard	64.0	18.70	10.7
	Phacelia	65.6	18.68	11.0
Cultivation with reverse compaction + ACSH	Stubble (reference)	66.0	18.63	10.8
	Straw	68.4	18.62	11.2
	Oiseed radish	68.3	18.80	11.3
	White mustard	64.4	18.84	10.8
	Phacelia	66.1	18.65	11.0
Direct seeding	Stubble (reference)	57.7	18.75	9.6
	Straw	58.7	18.77	9.8
	Oiseed radish	59.6	18.49	9.7
	White mustard	57.3	18.50	9.4
	Phacelia	59.3	18.68	9.9

Oilseed radish (*Raphanus sativus* var. *oleífera* Metzg) was used as a green manure crop in both crop rotations. Sowing was carried out in the second decade of June, when the conditions for temperature, light, and moisture were the most optimal for the rapid growth and accumulation of biomass plants. A 35–40 days later sowing, the biomass of oilseed radish was introduced into the soil using dump plowing to a depth of 22 cm.

Vegetation of oilseed radish helped to increase the total flow of CO_2 from the soil surface over this period. Indicators increased about 1.5 times compared to the control variant, regardless of experience and year of research. The exception was the 2016 data for experiment II, where the relative increase in the total CO_2 flux was 10%. Since the release of CO_2 from the soil with actively growing plants is associated mainly with respiration of the roots and rhizosphere microflora, this could be the result of a significant thinning of sowing against the background of a prolonged drought (Table 3.117).

Comparison of the results obtained simultaneously in the fallow and cropland, allowed us to estimate the proportion of root respiration and rhizosphere microflora in the total flux of CO_2 from the soil surface in the short-term cultivation of oilseed radish. The value of their joint contribution to the total CO_2 emissions during the growing season was 40–63%. Close estimates of the parameter (up to 50% of the total flux), obtained including isotope methods, are shown.

After plowing up the green mass of oilseed radish into the soil, the total CO_2 flux from its surface increased 1.4–2.3 times as compared with the control, and the differences in all years were statistically significant ($p < 0.05$). Relative to pure fallow, the increase in experience I for the period amounted to 106, 108 and 38%, respectively in 2015, 2016 and 2017. In experience II, the increase in flux over the years reached 130, 48 and 50%. A smaller increase of values in the variants with the green manure of both experiences in 2017 was apparently associated with unfavorable hydrothermal conditions for mineralization, especially temperature. As is known, the dependence of the rate of decomposition of organic matter on temperature is linear or exponential in nature. The low intensity of the mineralization processes in experience II under the conditions of 2016 could be due to the lower inflow of plant biomass in the soil due to sparse sowing. During the period of high availability of organic matter of plant origin, the contribution of soil organic matter to the outflow of CO_2 is insignificant.

Accounting for oilseed radish yielded estimated the amount of plant matter formed by its aboveground and underground biomass for a short period of cultivation (~ 40 days) in the conditions of the forest-steppe. The total biomass ranged from 170 to 705 g dry matter m^{-2}. Regardless of experience, the maximum yield of green manure crops was obtained in 2017, and the minimum – in 2016, which corresponds to the severity of the aridity period during the growing season of these years.

Table 3.117

The total CO_2 emission from the surface of gray forest soil in the field experiences (Sokolova et al., 2019)

Variant	Year	On the whole for the season (May – Sept)	In the periods of observation		
			before green manure planting	during green manure vegetation	after plowing green mass
Experience I					
1	2015	210 [194;230]	83 [75; 93]	81 [72;84]	49 [38; 61]
	2016	201 [192; 219]	89 [82; 98]	70 [63; 73]	46 [35; 57]
	2017	166 [154; 204]	52 [47; 76]	81 [74; 85]	52 [50; 53]
2	2015	301 [277;328]**	70 [68; 76]	124 [117; 149]**	102 [87; 112]**
	2016	266 [251; 301]**	64 [58; 76]	108 [102; 130]**	95 [80; 104]**
	2017	272 [247; 278]**	56 [49; 57]	130 [109; 137]**	72 [70; 75]**
Experience II					
1	2015	91 [79;105]*	20 [18; 24]	42 [35; 49]	29 [25; 31]*
	2016	173 [157; 182]	43 [42; 46]	77 [69; 85]	52 [43;54]
	2017	129 [127; 142]	44 [41; 54]	46 [40; 50]	42 [40; 44]
2	2015	143 [129; 156]*/**	21 [20; 24]	59 [45; 65]	67 [56; 79]**
	2016	214 [184; 231]**	46 [42; 50]	85 [83; 101]*	77 [72; 95]**
	2017	175 [164; 190]**	32 [32; 36]	75 [75; 87]**	63 [60; 64]**

Note: 1 – pure fallow; 2 – fallow with short-term sowing of oilseed radish. * statistically valuable ($p<0.05$) differences in years; ** statistically valuable ($p<0.05$) differences between variants.

The initial fertility of the soil had no less influence on the formation of productivity. So, in experiences I, where its level was higher, the yield of oilseed radish in all years was higher. The ratio of the above-ground mass / roots (6.7-9.6) indicates that in all years the flow of organic matter into the soil was provided by the green mass.

Due to the unequal productivity of oilseed radish in experiences, the parameters of net primary production (NPP) varied widely (81–197 g C m^{-2}). In half the cases, the photosynthetic carbon sink did not compensate for its loss due to respiration of heterotrophic microflora. As a result, a negative carbon balance was formed. The largest deficit (-128 g C m^{-2}) differed in the variant of fallow with short-term sowing of oilseed radish in experiences II under the conditions of 2016, when its productivity was low, and the loss of carbon due to the active mineralization of green mass and barley plant residues was significantly higher. High yields of green manure culture in the experiences of 2017, combined with unfavourable conditions for the mineralization of newly introduced organic matter, contributed to the formation of a positive carbon balance (+64 – +166 g C m^{-2}). Also positive (+26 g C m^{-2}) turned out to be a balance in the variant with the green manure of experience II in 2015, when the crop rotation field was located after the fallow. The reason could be a smaller stock and activity of the microbial pool in the absence of plant residues of the previous culture.

The carbon balance in the pure fallow, as is characteristic of this farming technique, was characterized by a significant deficit (-91 – -210 g C m^{-2}). Its value was influenced by the soil carbon resource and the pool of plant residues of the previous culture, which is confirmed by the data in literature. Short-term green manure of the fallow reduced the deficit, and when combined conditions that are favorable for plant growth, but unfavorable for the mineralization of their green mass, contributed to the formation of a positive carbon balance. The important role of green manure in carbon sequestration and replenishment of its reserves in soils in the semi-arid climate of even tropical regions is shown in.

Thus, the short-term green manure of the fallow in the conditions of the forest-steppe zone contributes to a significant change in carbon fluxes in the agroecosystem, not only by increasing its gaseous losses, but also by intensive accumulation of phytomass. Short-term cultivation of oilseed radish due to rapid growth can be considered an effective farming technique, since it reduces and/or completely compensates for the deficit in the carbon balance in comparison with pure fallow.

It was also established (Oliveira et al., 2017) that oil radish is a reliable source of macro and microelements in the soil as a result of their release during the decomposition of green manure in the soil. In 2013, the litterbags were placed directly on the soil surface, between onion rows. Twenty-four bags of each treatment were placed (six bags in each plot), for a total of 144 litterbags. Bags were secured on the ground by iron bars to prevent shifting in the wind. Bags were collected at the time of deposition (time 0) and at 15 and 45 days after deposition (DAD) of the litterbags. The bags were opened in the laboratory; the residue removed after the bag remained in the experimental area contained soil particles and poultry litter, given that the experimental area contains soil particle waste. The litter bags were opened in the laboratory and the remaining plant residues were removed, washed in distilled water and then in 0.1 mol L^{-1} HCl solution and again in distilled water. Residues were dried in a drying oven with circulation at 65 °C, weighed, ground and reserved for chemical fractionation of P in the tissue.

The other part of fresh shoot matter was homogenized, weighed, and placed in nylon fabric litterbags (0.40 x 0.40 m, with 2 mm mesh) (Tagliavini et al., 2007). The following amounts of fresh shoot matter were placed in separate litterbags: 235.13 g of WD, 767.99 g of BO, 434.50 g of RY, 460.46 g of RD, 570.67 g of RD + BO, and 416.82 g of RD + RY. These values, in terms of kg ha-1 of DM, amounted to 4620 WD, 5263 BO, 5060 RY, 3640 RD, 4030 RD + BO, and 3730 RD + RY, and they are equivalent to DM amounts obtained in the field at the sampling carried out on July 11, 2013. The other initial chemical characteristics of the residues and amounts of nutrients added to each treatment are shown in Table 3.118.

Residue DM was subjected to P chemical fractionation. The following P fractions were obtained: total acid-soluble P (TASP), soluble inorganic P (Psi), soluble organic P (Pso) (by the difference between TASP and Psi), lipid P (Plip), P associated with RNA (P-RNA), P associated with DNA (P-DNA), and the residual P fraction (Pres).

The distribution of P forms in plant tissue at time 0 (0 DAD) occurred in the following order of importance for all treatments: Psi > Pso ≈ Plip ≈ P-RNA > P-DNA ≈ Pres. The Psi form exhibited a content of 3068 ± 566 mg kg^{-1} in the overall average, representing approximately 73 ± 14 % of the total P content (Figures 3.25–3.26). In addition to total P concentration, the release of P from cover crop tissue also depends on the form of P accumulated in the tissue and the quality of the residue.

Table 3.118

Initial chemical characterization of weed (WD), black oat (BO), rye (RY), oilseed radish (RD), oilseed radish + black oat (RD + BO), and oilseed radish + rye (RD + RY) residues and added amounts of dry matter and nutrients (Oliveira et al., 2017)

Parameter	WD	BO	RY	RD	RD + BO	RD + RY
TOC	409.4 ± 1.02[1]	375,0 ± 0.40	401.0 ± 2.06	365.2 ± 1.21	369.7 ± 0.80	366.8 ± 1.50
N	26.2 ± 0.17	19.8 ± 0.21	18.0 ± 0.19	22.3 ± 0.37	21.9 ± 0.34	24.2 ± 0.22
P	5.5 ± 0.12	6.0 ± 0.02	5.7 ± 0.02	6.5 ± 0.06	6.6 ± 0.01	6.6 ± 0.01
K	21.5 ± 0.10	42.9 ± 0.59	24.9 ± 0.30	33.4 ± 0.45	36.3 ± 0.32	33.0 ± 0.81
Ca	4.9 ± 0.10	3.5 ± 0.04	6.4 ± 0.12	6.9 ± 0.06	10.4 ± 0.11	8.0 ± 0.16
Mg	1.9 ± 0.05	1.6 ± 0.03	2.1 ± 0.11	2.1 ± 0.01	4.6 ± 0.05	2.6 ± 0.04
Cel	182.3 ± 1.02	239.6 ± 7.21	161.8 ± 7.59	211.0 ± 2.87	220.7 ± 2.34	192.9 ± 1.12
Lig	69.2 ± 0.77	86.1 ± 2.23	102.8 ± 5.33	71.7 ± 1.63	93.5 ± 2.41	80.6 ± 0.63
Bio	748.4 ± 1.28	674.3 ± 5.78	735.5 ± 9.01	717.3 ± 4.09	685.6 ± 4.19	726.5 ± 1.57
C/N	16 ± 0.99	19 ± 1.93	22 ± 2.32	17 ± 2.72	17 ± 2.50	15 ± 1.53
Lig/N	3 ± 0.17	4 ± 0.21	6 ± 0.19	3 ± 0.37	4 ± 0.34	3 ± 0.21
C/P	75 ± 14.82	62 ± 2.61	70 ± 5.36	56 ± 4.91	56 ± 6.28	56 ± 7.59
Cel/Lig	3 ± 0.17	3 ± 0.21	2 ± 0.19	3 ± 0.37	2 ± 0.34	2 ± 0.22
Added amount (kg ha^{-1})						
DM	4620.0	5263.1	5060.0	3640.0	4030.0	3730.0
TOC	1891.6	1973.7	2029.0	1329.4	1490.1	1368.0
N	120.9	104.4	91.1	81.1	88.3	90.2
P	25.2	31.7	28.8	23.9	26.6	24.5
K	99.2	225.8	126.0	121.5	146.2	123.1
Ca	22.4	18.6	32.2	25.0	42.0	29.8
Mg	8.8	8.4	10.9	7.7	18.7	9.8

[1]Mean ± standard deviation (n = 4). Cel: cellulose, Lig: lignin, Bio: no structural biomass, DM: dry matter, TOC: total organic carbon.

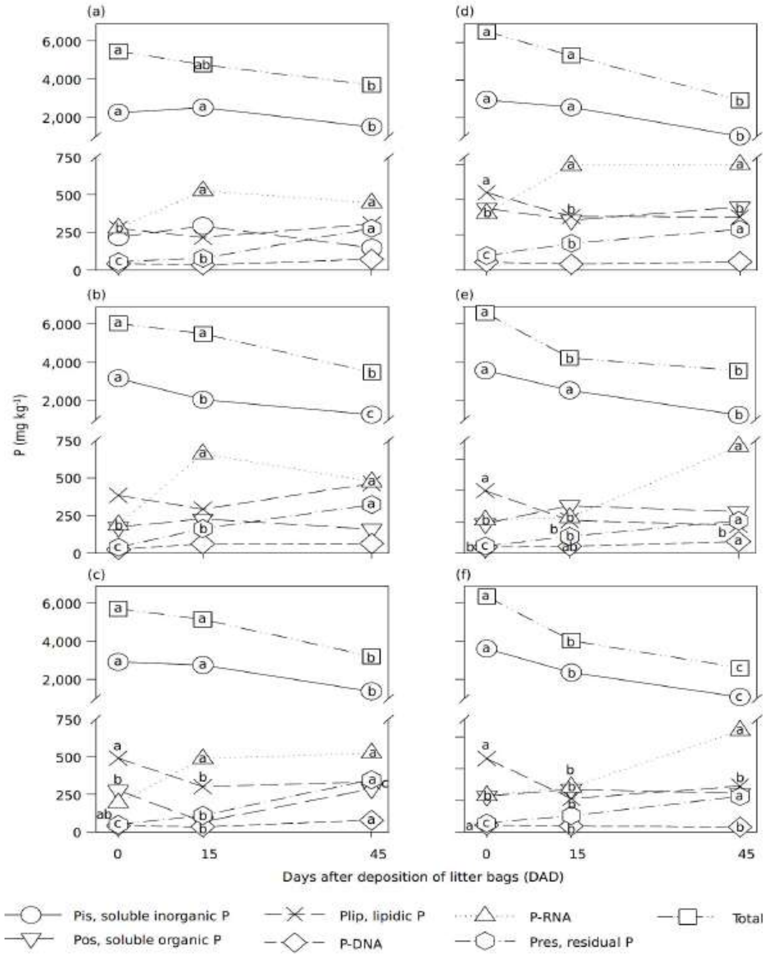


Figure 3.25 – Changes in phosphorus forms (a) in residues of weeds (WD); (b) black oat (BO); (c) rye (RY); (d) oilseed radish (RD); (e) oilseed radish + black oat (RD + BO); and (f) oilseed radish + rye (RD + RY) at 0, 15, and 45 days after deposition (DAD) of the litterbags on the soil surface in agroecological no-till onion. Means followed by the same letter in DAD do not differ by the Tukey test (*p<0.05*) (Oliveira et al., 2017)

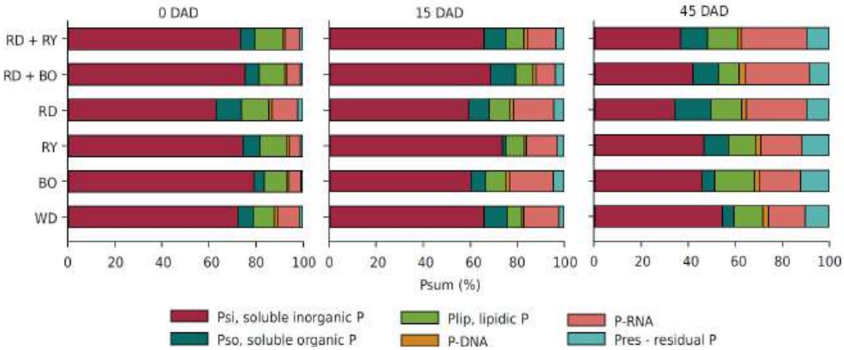


Figure 3.26 – Relative percentage of P fractions in the plant tissue of the residues of weed (WD), black oat (BO), rye (RY), oilseed radish (RD), oilseed radish + black oat (RD + BO), and oilseed radish + rye (RD + RY) extracted by chemical fractionation in cover crop residues at the time of deposition of cover crop residues on the soil (time 0) and at 15 and 45 days after the deposition (DAD) of litterbags on the soil surface in agroecological no-till onion (Oliveira et al., 2017)

The highest accumulation of P in cover crops occurred in the soluble inorganic P fraction, which is the fraction of fastest release in the tissue of all the plants.

Black oat had the highest initial release rate of soluble inorganic P, but the rate became equal to the release rate of other cover crop residues at 45 days after deposition. However, weeds released only half the amount of soluble inorganic P in the same period, despite accumulating a considerable amount of P in their biomass.

The oilseed radish + rye and oilseed radish + black oat mixtures showed a higher release of P-RNA at 45 days after deposition compared to the single treatments.

The effectiveness of the sideral mass as a reserve of macro and microelements in the soil was also confirmed in the studies of Antonets et al. (2010), who notes that the use of sideral crops is a significant replenishment of the soil with basic nutrients, which improves the mineral nutrition of plants. The agrochemical characteristics of siderate plants are given in the Table 3.119.

Table 3.119

Agrochemical characterization of green manure plants using the calculation-equivalent method (Antonets et al., 2010)

Green manure	Yield green mass, c ha^{-1}	Accumulated in the total biomass of nutrients, kg ha^{-1}			Total, kg ha^{-1}	In gross mass, kg ha^{-1*}
		N	P_2O_5	K_2O		
Sainfoin	275	145	25	75	245	510.4
Winter vetch	250	160	75	200	435	906.3
Rye-oat mixture	275	120	35	80	235	489.6
Buckwheat for two earnings	650	200	135	305	640	1333.3
White mustard	250	60	40	90	190	395.8
Suripa	340	135	55	240	430	895.8
Oilseed radish	450	85	65	245	395	822.9
Phacelia	300	80	50	200	330	687.5

1* Calculation of the amount of the active substance in fats is based on its content in the complex mineral fertilizer – nitroammophos.

The materials in the table show that the use of sider crops (as organic fertilizers) ensures the accumulation of a significant amount of nutrients. Thus, after two crops of buckwheat, the soil accumulates about 640 kg/ha of N, P_2O_5, K_2O. A significant amount of these macronutrients also remains after spring and winter vetch, suripa, oil radish, phacelia, and safflower. Undoubtedly, the largest amount of biological nitrogen remains after such leguminous crops as spring and winter vetch, asparagus, although with two earnings of buckwheat biomass, this indicator is also significant.

Buckwheat is characterized by the ability to assimilate difficult-to-dissolve macroelements, in particular, phosphorus, and convert them into readily available forms used by other plants. By converting the active substance of the main nutrients listed in the table into the physical mass of mineral fertilizers (weights), we get the volume of fertilizers that mainly provide the recommended regime of mineral nutrition of the main agricultural crops.

Thus, increasing the specific mass of biological nitrogen and other nutrients in agroecosystems due to the expansion of siderate areas (primarily leguminous sideral crops) is an important lever for stabilizing productivity, energy and economic efficiency of agriculture.

The author of the study (Antonets et al., 2010) emphasizes that green manure is one of the main factors of the organic farming system. This measure is mandatory in the transition from intensive to organic farming. Its use enriches the soil with organic matter, increases the amount of nutrients, and generally improves soil fertility and profitability. The use of green manure virtually eliminates the need for additional mineral fertilizers, which is an environmentally and economically sound measure. All of this ensures an increase in production profitability, contributes to the ecological rehabilitation of the soil, and improves its fertility based on biological principles of farming and environmental protection. The organic farming system has developed and uses methods to maximize the use of solar energy by covering the soil with plants almost throughout the entire growing season. Crops of main crops, green manure, vetch-oat mixture, and cereal crops form a permanent soil cover, which increases the utilization rate of incident solar radiation energy by maximizing the activity of the plant photosynthetic apparatus.

The technologies for growing oil radish as a green manure have been developed by the Union of Organic Agriculture (Union of Organic Agriculture, 2022). According to their data, the most difficult conditions for oil radish green manure are during its cultivation in the post-harvest period (July-August), which is characterized by the greatest moisture deficit in Ukraine. Its reserves in the 0–10 cm layer on the black soils of the Central Forest-Steppe are 3–8 mm and much less in other, less fertile, soil types. In order to prevent complete evaporation of water from the soil intended for green manure, it is necessary to apply surface tillage, consisting of disking the soil by 5–6 cm, harrowing and rolling the surface with ring rollers, together with harvesting the predecessor and, as an exception, one day after harvesting. Such tillage, especially at night, destroys the capillaries between the upper tilled and lower untilled, more moistened layers (from which water rises up through the capillaries), which stops its evaporation and contributes to the gradual moistening of the upper layer.

Another, less effective source of soil surface moisture during this period is dew that falls as a result of water vapor condensation (after the soil temperature drops at night and the surface air cools). The layer of dew formed overnight reaches 0.1 to 0.5 mm. And in a year, it falls up to 40 mm, which is the amount that corresponds to the monthly precipitation rate in the Central Forest-Steppe in April or August-November. Many factors influence the formation of dew and its amount, including wind. If it has a low speed, then new portions of water vapor rise to each object (lumps, plants) on which dew settles, which increases the amount of moisture. Dew does not form when the wind is strong. Dew forms mostly on a flat, but rough, soil surface, which is the case with the technology of directed surface tillage for green manure. But most modern agronomists are not familiar with these production and natural features. That is why they are in no hurry to create the right conditions for green manure production, believing that green manure will grow even under late tillage, and at the first failure they conclude that green manure is inappropriate.

Figure 3.27 – Seed mixtures of siderates, which include oilseed radish seeds

The generalized recommendations of the authors (Table 3.120) for oil radish green manure in the zone of sufficient moisture are reduced to the implementation of the above-mentioned soil preparation methods in a short time, the use of nitrogen fertilizers (30–60 kg ha^{-1}), high-quality seeds with their mandatory treatment before sowing and the incorporation of green manure to a depth of 15–30 cm. This technology helps to preserve the remaining water in the soil that was not used by the predecessor, promotes the accumulation of water in the surface soil layer by rising from the lower layers, which ensures the emergence of full germination of plants in 3 to 4 days after sowing, and their dense grass stand is an environment for the formation of a large amount of dew, which saves plants from death in the first days of the growing season.

Table 3.120

The main technological parameters of the use of oil radish as a siderate (generalization of the author of the monograph)

Technological components	**Parameters**
1	2
The optimal crops for this green manure	All non-cruciferous vegetables, potatoes, sugar and fodder beets, spring cereals, garden aisles (stone fruits and pome fruits)
Sowing dates for green manure	The widest range is from the end of March to the second decade of September, depending on the type and nature of green manure
Terms of green manure	No later than 30 days before sowing the next crop
Preparing the soil for sowing green manure	Option for surface cultivation to a depth of 8–10 cm. In dry season, post-sowing rolling
Seeding rate	The recommended seeding rate is 2.0–2.5 million germinating seeds/ha with a row spacing of 15–30 cm, or a spreading (continuous) seeding rate of 2.5–3.0 million germinating seeds/ha. In dry conditions, the rate is increased by 25-40% at the time of sowing. The use of dosed seed packets per 1 hectare of sowing is also possible (Fig. 3.30)
Preparation of seed material	The seeds are treated against pests (in particular cruciferous fleas, especially during summer sowing) with the recommended preparations
Possibility of compatible sowing with other crops	It is possible to use green manure mixtures with other cruciferous and leguminous components
Sowing depth of green manure	From 3 to 5 cm depending on the mechanical composition of the soil and soil moisture conditions
Fertilizing green manure	Recommended doses of N 30–60 kg/ha
The optimal phase of green manure production	Depends on the nature of the green manure: as a component of organic fertilizer from the budding to flowering phase; as a green mulch – stemming – budding. On poor soils during winter sowing from the budding phase to the fruiting phase («green pod»)

(End of Table 3.120)

1	2
Depth of green manure production	15–30 cm, depending on the type of soil and subsequent crop, or intensive mixing of the cider with the topsoil of 8–12 cm
The method of green manure	Embedding in the soil; mulching with dried leaf and stem mass with subsequent embedding; mulching with dried parts of stems in a crushed or whole state with subsequent embedding in the soil
The need for preliminary preparation of green manure	Required. We recommend 1–2 disking to a depth of 8–12 cm or mowing. In the case of combined modern machines, the need for final tillage is minimal. On private plots, mowing with the mass of the crop followed by plowing or sowing green manure before winter with the residues in the spring is used
Requirements for the humidity regime of green manure	It is advisable to plow into moist soil or during periods of sufficient atmospheric moisture. Plowing in dry soil or during prolonged soil drought is undesirable and inefficient

Even the smallest rains (3–5 mm), which are considered ineffective in agronomy, are very useful for post-harvest siderates. Further, more abundant rains (up to 10 mm or more) moisten the soil first to a depth of 15 cm, and later to the entire depth of the root layer. Such conditions, combined with warm weather in July and September, contribute to its intensive growth, prevent the reproduction of weeds and pests. In case of insufficient soil moisture, dew provides especially great help to the young siderate plants of oil radish, because only it saves the plants from death in dry, hot weather, and when it falls from the plants, it improves the moisture of the soil surface and subsoil air.

In the zone with less stable moisture, direct sowing of oil radish with stubble seeders without pre-sowing soil preparation deserves attention.

Mixtures of oil radish with other fodder crops (oats, peas, diapers, etc.) as siderate are mostly needed in farms with developed animal husbandry, where sideration is combined with strengthening the fodder base.

It is recommended to mow the green mass of oilseed radish for siderate during the period of budding before the beginning of flowering, when it contains the largest amount of nitrogen. It is also necessary to take into account the difficulties of wrapping oil radish biomass in the soil. A large land mass (200 t/ha and more) is poorly incorporated into the soil, the quality of plowing is unsatisfactory. With a high mass yield, the field is cultivated with disc tools in one or two tracks. After 3–4 days after the siderate has dried, peeling or disking is carried out again, and then plowing according to the generally accepted technology.Siderate with a small biomass is plowed directly. The following technology is also recommended: the siderate is rolled with smooth rollers, after which the plowing is carried out in the direction of the passage of the rollers.

Research conducted at the Podillia Institute of Forage and Agriculture of the National Academy of Sciences (Getman, 2007) shows that when growing oil radish in post-harvest crops, preparation of the soil after harvesting the predecessor is important (Table 3.121). It should also be remembered that the cabbage species included in the post-harvest mixtures have small seeds, and therefore, to guarantee friendly seedlings and uniform wrapping of the seeds during sowing, it is necessary to level the soil carefully. The choice of the method of cultivation depends on the condition of the soil, its weediness and humidity. In weather conditions, when the upper layer of the soil is wet, and the lower layer is dry, it is advisable to carry out surface treatment with combined aggregates (AG–2.4, AKG–6, APB–6, RVK–3.6, «Europak», etc.), which makes it possible to combine several tillage operations. At the same time, the terms of work are shortened, which prevents the upper layer from drying out, and the seeds fall into moist soil. In the absence of the above-mentioned technical means, disking is carried out to a depth of 10–12 cm with subsequent cultivation and pre- and post-sowing soil rolling. It should also be noted that the use of combined units makes it possible to reduce fuel consumption by 1.5–2 times compared to plowing.

Mineral fertilizers are applied in a dose of $N_{30-90}P_{30-45}K_{30-60}$, or nitrogen – N_{30-90}. In the steppe zone and, especially, in its southern regions, on irrigated lands, one more harvest can be obtained during this period.The irrigation regime consists of pre-sowing irrigation of 500 m^3 and 2–3 vegetation irrigations at the rate of 400–450 m^3 ha^{-1}.

Table 3.121

The influence of soil cultivation methods on the yield of post-harvest oil radish, c/ha (Shuvar, 1994)

Method of soil cultivation	Fuel consumption for basic tillage	Leaf and stem mass	Dry matter	Digestible protein
Plowing	19.6	221	22.1	4.0
Disking	5.4	195	20.1	3.9
Chiseling	6.2	198	20.0	3.9
Cultivation	5.1	196	19.3	3.8
Stubble sowing	0	165	17.1	3.5

On soils supplied with phosphorus and potassium, only nitrogen fertilizers are used in the dose of $N_{45–60}$ in post-harvest crops. Sowing of oil radish in post-harvest crops must be completed by August 15. Later sowing times, especially in the Forest Steppe and Polissia, lead to a 20–30% decrease in productivity. Sowing rates of oil radish in single-species crops are 2.0–2.5 million seeds per hectare, in mixtures 50–70% of the full sowing rate. Mixtures are sown in the usual row method to a depth of 2–3 cm for oil radish. In addition, it is necessary to pay special attention to the cutting height of the predecessor; too high stubble can become a serious obstacle when working the soil, especially the surface, and further complicates the work of planters and reduces the quality of sowing. It is desirable to reduce to a minimum the break between harvesting the precursor and sowing of post-harvest crops, using minimal tillage (disking, chiselling) or combined tillage-sowing units instead of plowing. With sufficient humidity of the upper soil layer, direct sowing on stubble is possible with seed drills with disc coulters (Figures 3.28–3.29). In general, summarized recommendations on the technology of sowing post-harvest fodder crops where one of the components is oil radish are presented in Table 3.122.

As a result, all the positive features mentioned above allowed oil radish to occupy a prominent place in the recommended mixtures for the main soil and climatic zones of Ukraine (Table 3.123, Figure 3.30) and typical schemes of the green conveyor for the Forest-Steppe zone (Table 3.25), as well as to be recommended in all terms outlined by agrarian science for intermediate crops and even in winter sowing options.

Table 3.122

Technological scheme of growing oil radish in post-harvest and post-harvest crops in single-species and multi-component versions

Sowing option	Technological parameters
Post–harvest sowing	Sowing should be completed by August 1–5. Preference should be given to stubble predecessors, or one–year fodder mixtures for fodder where cruciferous components were absent. The rate of sowing in its pure form is 2 – 2.5 million pcs./ha of similar seeds, pre–poisoned, from seedling pests, seeds (insecticide treatment) with a row spacing of 15 – 19 cm, depending on the type of seeder and sowing. The method of sowing is mainly the usual row sowing. The rate of sowing in the composition of mixtures according to their structural formula is increased by at least 10–15%. Sowing depth for oil radish is 2 – 4 cm. Rolling after sowing, under the conditions of a dry period, is mandatory. The principle of soil preparation for sowing is to focus on the most small–seeded crop included in the mixture. Preference should be given to moisture–saving surface tillage systems based on the principle of controlled mulching with plant residues of the predecessor and the implementation of pre–sowing preparation and sowing in a single technological cycle. Application of mineral fertilizers under pre–sowing treatment for phosphorus and potassium and, if possible, fractionally for nitrogen. The dose of fertilizers is determined by the complex of conditions of soil fertility, abiotic factors of the environment and the composition of the mixture and varies within N30–90P30–60K30–60. It is possible to adjust the doses of fertilizers based on the removal of nutrients by new (previous) and intermediate (next) cultures. On soils sufficiently supplied with phosphorus and potassium, only nitrogen fertilizers are applied.Nitrogen fertilizers are used mainly in the form of top dressing in the peak period of linear growth of these crops for mixtures in which, together with oil radish, cereal components prevail. In the case of the presence of leguminous components in the mixture – N15–30P30–60K30–60. Preference should be given to factory mixtures of fertilizers. Applying fertilizers is advisable under the conditions of a minimum level of atmospheric moisture and certain parameters of the GTC of the period from the collection of the predecessor to the beginning of the harvest maturity of the crop (precipitation at least 50–60 mm, GTK at least 0.75–1.0)
Post–harvest sowing	Sowing should be completed by August 15 after stubble ultra early maturing and early maturing predecessors that vacate the field early. Mowing the predecessor on low stubble. The maximum gap between harvesting the precursor and sowing the intermediate crop under conditions of sufficient technological soil moisture is 2–3 days. Preference should be given to surface tillage systems in a combined combination of loosening operations with maximum preservation of plant residues and sowing with post–sowing rolling or in the option of direct sowing. The rate of sowing in its pure form is 2.5 – 3.0 million pcs./ha of similar seeds with a row spacing of 15 – 25 cm, depending on the type of seeder and sowing. The method of sowing is mainly the usual row sowing. The seeding rate has been increased by at least 15–25%. It is recommended to treat the seeds with systemic insecticides to protect against seedling pests. Sowing depth for oil radish is 2–4 cm. Rolling under conditions of a dry period is recommended before sowing and mandatory after. Features of fertilization and their adaptive substantiation are similar to those for the option of post–harvest sowing.

Figure 3.28 – Seedlings of oil radish obtained in direct sowing options, 2011

Figure 3.29 – The yield of green mass of oil radish for sowing on August 18 is 212 t/ha (Likhochvor, 2008)

Table 3.123

Grass mixtures of post-harvest crops of multipurpose use for zones of Ukraine (sowing rates, million/ha) (Kovbasyuk, 2011)

Zone	Variants of mixtures with oilsed radish for post-harvest sowing
Forested	*• corn (0.3 – 0.4) + sunflower (0.1 – 0.2) + yellow lupine (0.4 – 0.5) + oilseed radish (1.6 – 1.9) • corn (0 .3 – 0.4) + sunflower (0.1 – 0.2) + field peas (0.4 – 0.5) + winter vetch (0.6 – 0.8) + oilseed radish (1.6 – 1.8) • barley (2.4 – 2.6) + corn (0.1 – 0.2) + field peas (0.3 – 0.4) + winter vetch (0.6 – 0.8) + white mustard (1.0 – 1.1) + oilseed radish (0.8 – 1.0) • oats (1.6 – 1.8) + fodder sorghum (1.0 – 1.2) + field peas (0.5 – 0.6) + white mustard (0.8 – 1.0) + oilseed radish (0.9 – 1.1)*
Forest steppe	*• barley (2.5 – 2.7) + oats (1.2 – 1.3) + field peas (0.5 – 0.6) + winter vetch (0.6 – 0.7) + oilseed radish (0 .9 – 1.2) + white mustard (0.8 – 1.0) •barley (2.4 – 2.6) + fodder sorghum (0.9 – 1.0) + fodder beans (0.3 – 0.4) + white mustard (0.9 – 1.1) + oilseed radish (1.0 – 1.2) • oats (2.5 – 3.0) + barley (1.0 – 1.2) + field peas (0.5 – 0.7) + oilseed radish (1.7 – 1.9) • fodder sorghum (1.3 – 1.4) + corn (0.1 – 0.2) + sunflower (0.1 – 0.2) + field peas (0.6 – 0.7) + oilseed radish (1.7 – 1.9)*
Steppe (for irrigation)	*• corn (0.3 – 0.4) + oats (1.3 – 1.5) + winter vetch (0.9 – 1.2) + field peas (0.2 – 0.3) + oilseed radish (1 .7 – 1.9) • corn (0.3 – 0.4) + barley (1.5 – 1.7) + plantain (0.8 – 1.0) + white mustard (0.9 – 1 ,0) + oilseed radish (1.1 – 1.3) • corn (0.3 – 0.4) + oats (1.4 – 1.6) + sorghum (0.5 – 0.7) + spring vetch (0.6 – 0.8) + oilseed radish (1.0 – 1.2) + winter rape (1.2 – 1.3) • corn (0.3 – 0.4) + fodder sorghum (0.9 – 1.1) + field peas (0.5 – 0.6) + winter vetch (0.8 – 1.0) + winter turnip (1.0 – 1.2) + oilseed radish (1. 0 – 1.2) • fodder sorghum (1.6 – 1.7) + corn (0.1 – 0.2) + oats (0.6 – 0.7) + seed sorghum (0.6 – 0, 7) + winter vetch (0.8 – 1.0) + white mustard (0.9 – 1.1) + oilseed radish (0.9 – 1.1)*

Due to their high ecological stability, the cultures indicated in the Table, unlike traditional fodder plants, intensively build up biomass until late autumn and make it possible to extend the green conveyor for 3–4 weeks. They withstand a short-term drop in temperature to minus 5–7 °C and are used until the first decade of November, and in some years – during the month of December. As high-protein crops, annual mallow, amaranth, oilseed radish, spring and winter rapeseed are excellent components for cereal crops that are unbalanced in terms of digestible protein – corn, oats, sorghum, rye.

Figure 3.30 – Variants of summer post-harvest sowing of horseradish in the conditions of the experimental hospital of the Institute of Fodder and Agriculture of the Podillia National Academy of Sciences, 2014

Table 3.124

A typical scheme of a green conveyor for cattle (forest-steppe zone) (Zinchenko, 2005)

Sources of green fodder	Sowing terms	Terms of use
Natural pastures	–	10.5–20.10
Winter rapeseed + winter rye	15–31.8	25.4–15.5
Winter rye + woolly vetch	25.8–5.9	10–25.5
Winter wheat + woolly vetch	25.8–5.9	20.5–10.6
Alfalfa, asparagus, clover + perennial cereals	Past years	20.5–15.6
The first bunch of perennial grasses	Past years	10–25.7
The second row of perennial grasses	Past years	10–20.9
Perennial grasses with four to five slope irrigation	Past years	20.5–10.10
Oats + legumes + oil radish of the first sowing period	10–20.4	15–30.6
The same for the second sowing period	25–30-4	1–15.7
Oilseed radish as clean crops	10.4–10.5	1.6–1.7
Corn + Sudan grass	5–10.5	15–31.7
Ottawa Sudan grass	5–10.5	10–25.9
Corn + soy	15–25.5	10–31.8
Corn + Sudanese grass + plantain	5–10.6	20.8–5.9
Ottawa Sudan grass	5–10.6	20–30.9
Corn (after autumn) after rye + vetch + oilseed radish	1–10.6	20.8–10.9
Corn or Sudanese grass (after autumn) after wheat + woolly vetch + oilseed radish	20–25.6	15–30.9
Corn + oilseed radish (subsequently)	20–25.7	20.9–10.10
Ottawa natural haymakers	–	10.8–10.10
Late autumn sowing of oilseed radish	1–10.8	10.9–10.10
Forage pumpkins	10–15.5	1.9–20.11
A bunch of root crops	10–20.4	10.9–31.10

The possibility of using oil radish as an intermediate crop is determined by the timing of its sowing and the temperature regime of the period of residual vegetation after harvesting the main crop (Table 3.126). In addition to this, according to the generalization of Kovbasyuk (2011), an important factor that determines the possibility and expediency of growing fodder crops in intermediate crops is the moisture indicator during the growing period – the hydrothermal coefficient (HTC). The optimal value of GTK for post–harvest and post–harvest crops is 1.4–1.6 and higher, satisfactory – 1.0–1.4, unsatisfactory – 0.6. With the value of GTK – 0.6, it is economically impractical to grow post–harvest and post–harvest crops. With such moisture, types of intermediate crops are grown only under irrigation.

Table 3.125

Productivity of spring crops in intermediate crops (Rakhmetov et al., 2008)

Crop	Productivity of above-ground mass, t ha^{-1}	Yield of absolutely dry mass, t ha^{-1}	Protein yield, t ha^{-1}
Oilseed radish *(Raphanus sativus L. var. oleiformis Pers.)*	40–65	5–7	1,1–1,3
Rocket crass *(Brassica campestris var. oleifera f. annua L.)*	30–40	3–4	0,6–0,7
Spring rape *(Brassica napus var. oleifera f. annua D.C.)*	40–45	5–6	1,0–1,1
White mustard *(Sinapis alba L.)*	35–42	4–5	0,7–0,8
Sarepta mustard *(Sinapis juncea Czern.)*	36–44	4–5	0,8–0,9
Malva melyuka *(Malva meluca Graebn.)*	44–62	6–8	1,4–1,5
Amaranth *(Amaranthus caudatus L.)*	40–55	5–7	1,2–1,3

Also important is the fact that oilseed radish is characterized by a less pronounced, to a certain extent, regular dynamics of a decrease in overall productivity when the sowing period changes from early spring to late summer (Table 3.127).

Table 3.126

The possibility of growing cruciferous crops in intermediate crops depending on the time of their sowing (Shpaar, 2006)

Crops	Days from sowing to the transition of the average daily air temperature below + 5 ^{0}C				
	more 80	80 – 76	75 – 71	70 – 65	65 – 60
Oilseed radish	+ +	+ + + +	+ +	+ +	+
Spring rape	+ +	+	+ +	+	+
Winter rape	+ +	+ +	+ +	+	+
Rocket crass	+ +	+ +	+ +	+	–
White mustard	+ +	+ +	+ +	+ +	+
Turnips on green mass	+ +	+	+	+	–

"++" – for green fodder and silage; "+ "– for green fodder; – cultivation is impractical

Table 3.127

The influence of sowing dates on the yield of intermediate crops of cruciferous crops (Shpaar, 2006)

Sowing date	Unit of measurement	Oilseed radish	Spring rape	Winter rape	White mustard
15.07	c ha^{-1}	346	277	383	169
	in % to the first term	*100*	*100*	*100*	100
22.07	c ha^{-1}	374	289	341	234
	in % to the first term	*108*	*104*	*89*	138
29.07	c ha^{-1}	367	297	284	255
	in % to the first term	*106*	*107*	*74*	151
05.08	c ha^{-1}	230	180	197	167
	in % to the first term	*66*	*65*	*51*	99
12.08	c ha^{-1}	199	160	140	172
	in % to the first term	*58*	*58*	*37*	102
19.08	c ha^{-1}	107	80	58	92
	in % to the first term	*31*	*29*	*15*	54

The Ministry of Agrarian Policy and Food of Ukraine also in its recommendations (Kvitko et al., 2010) regarding the optimal composition of fodder mixtures for Polissia and the Forest-Steppe zone assigns a significant role to oil radish. The composition of the recommended mixtures is as follows: 1) corn in mixtures with cruciferous vegetables or a mixture of corn with soy; 2) barley + oats + peas; 3) oats + peas + oilseed radish; 4) oats + white mustard + peas; 5) oats + white mustard; 6) oats + oilseed radish; 7) oats + oilseed radish + peas, etc.

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CHAPTER 4. APPLICATION OF OILSEED RADISH FOR WEED CONTROL AND REDUCTION OF SEGETAL SOIL DEGRADATION

4.1. Potential of oilseed radish herbicide competition

An oilseed radish is a well-known culture in Europe, the USA and Canada with a multifaceted nature of implementation. The multipurpose study of this species in different soils and climatic zones made it possible to formulate the main positive features potentially inherent in this plant: unpretentious to the conditions of cultivation and precursor in crop rotation (Oliveira A. et al., 2011), highly productive and nutritious, productive in after–use and post–harvest use (McCartney et al., 2009), highly intensive functioning of the root system, relatively tolerant to changes in the sowing time, marked by the rapid growth, with a high positive reaction to mineral fertilizers (Tsytsiura, Tsytsiura, 2015), highly competitive in vegetation growing in grain fields, suitable for the productive multicomponent use within forage mixtures with a wide range of accompanying crops (Dean and Weil, 2009; Malézieux, 2009), suitable for the multipurpose use (green mass, silage, haying, green manure, grass meal) (Larkin and Griffin, 2007; Davies et al., 2008), positive impact on the phytosanitary and nutrient regime of the soil, a good meliferous plant, and it is a means of revitalizing the fertility of depleted soils as a substitute for organic fertilizers by biomass ploughing (Lehrsch and Gallian, 2010; Mazzoncini et al., 2011), with high nematode resistance (Vleugels et al, 2014; Teklu et al., 2014), highly competitive against weeds (Lawley et al., 2011; Brust et al., 2014; Kunz et al., 2016), used as feedstock for biofuel production (De Andrade Avila and Sodre, 2012; Ratanapariyanuch et al., 2013) and its honey productivity (Decourtye et al., 2010).

On the one hand, regardless the above mentioned feature of this culture to suppress weeds (Lawley et al., 2011; Brust et al., 2014; Kunz et al., 2016), the issue of the effective control over weeds in its agrophytocenoses is the topical one that seek to exploit possible technological options of wide rows growing, especially for seed purposes, a rapid growth and ripening, a tendency to lay down in the final vegetation, starting from the fruiting stage.

All these factors in growth peculiarities and crop development stipulate an intensive decrease in the competitiveness of oilseed radish plants in the second vegetation period of this radish (Tsytsiura, Tsytsiura, 2015).

On the other hand, despite the technological level of the basic crops cultivation, weeds remain a significant and complex problem that restricts the effective realization of the genetic potential of varieties and hybrids of the agricultural crops (Szumigalki et al., 2005; Fennimore et al., 2008; Yaduraju et al., 2018). However, weeds are an integrated component of the overall functional life of any agrophytocenosis, and they cannot be considered separately from the total resulting bioproductivity (Cousens et al., 1995; Mortensen et al., 2000; Rola et al., 2002; Franke et al., 2009; Shaner et al., 2014). The latter statement is determined by the nature of any crop sowing as a complete multicomponent agrophytocenosis. Moreover, it has been put foraward to use the notion of an agrocenotic gradient as a certain organized sequence of fields occupied by different cultivated plants (Mirkin, 1985; Jordan, 1993; Monaco et al., 2002; Zimdah, 2007; Bajwa et al., 2017). Separate gradations of this gradient can be distinguished as sowing of the same crop. This approach corresponds to another definition of the agrophytocenosis, according to which agrophytocenosis is a plant grouping of "an arable land, a set of cultivated plants, changing during rotation or maintained as monoculture, and weeds united in a vegetative grouping" (Grodzinski, 1992; Rao, 2017). It is the emphasis on the latter statement in terms of the vegetative grouping that presents a tendency in the modern science, regarding the formation of weed levels and their detriment (Cardina et al., 1997; Fennimore et al., 2008; Dobrzański et al., 2009; Shaner et al., 2014).

The well–known practice of the role of weeds in crops is regard as an element unnecessary in crops, which at different densities and species composition can reduce crop yields in the range from 5 to 80% (Aldrich, 1987; Bruce et al., 1992; Callaway et al., 1993; Rao, 2000; Oerke et al., 2004; Jakubiak, 2005; Týr et al., 2009; Booth et al., 2010; Kraehmer et al., 2013; Abouziena et al., 2014; Korav et al., 2018; Singh et al., 2018; Westwood et al., 2018). There is also a risk of weed spread and growth due to the climate change and the emergence of weed resistance to a number of herbicides (Zimdahl et al., 2004; Kathiresan et al., 2005; Ziska et al., 2011; Kathiresan et al., 2012; Ervin et al., 2014; Singh et al., 2015; Liebman et al., 2016; Moss et al., 2017; Jugulam et al., 2019). An integral aspect of the effective crop weed control is also taking into account the current trends in soil tillage systems, fertilizer levels and intensity of herbicide control, crop rotation systems and mechanization level, etc. (Harker et al., 2013; Singh et al., 2015; Tursun et al., 2015; Liebman et al., 2017). In addition, recent studies have shown that weeds are to be regarded as inherent components of the agrophytocenosis, which perform additional positive functions in the overall trophic structure of the connections between its components (Cardina et al., 1997; Singh et al., 2006; Burgos et al., 2015; Rana et al., 2016). A complex mechanism of allelopathic effects of weeds on cultivated plants as well as on each other within different species and biological groups has been traced (Grodzinski, 1973; Kandasamy et al., 1997; Batish et al., 2002; Khanh et al., 2005; Sangeetha et al., 2015; Jabran et al., 2015).

In brief, the weed control is one of the complex and responsible parts in the overall technological management of growing all crops.

A common tactic for weed control and a number of control measures has been developed for a fairly long period of the scientific research, and it is based on establishing a critical weed control period especially for the crop (Nieto et al., 1968; Weaver et al., 1992; Berti et al., 1996; Singh ET AL., 1996; Knezevic, 2000; Rajcan et al., 2001; Singh et al., 2002; Knezevic et al., 2002; Jakubiak et al., 2006; Knezevic et al., 2015; Swanton et al., 2015; Andrew et al., 2015). So, today this indicator has been identified and analyzed for many crops (Hall et al., 1992; Norsworthy et al., 2004; Maqbool et al., 2006; Ahmadvand et al., 2009; Cardoso et al., 2011; Karkanis et al., 2012; Tursun et al., 2016; Vaishali et al., 2018) including relatives (Brassicaceae) to oilseed radish crops – a radish, a spring rapeseed, a winter rapeseed and a mustard (Martin et al., 2001; Singh et al., 2006; Paulsen et al., 2006; Hamzei et al., 2007; Beckie et al., 2008; Roshdy et al., 2008; Qasem et al., 2009; Lemerle et al., 2010; Harris et al., 2015). The conceptually indicated methodological approach allows us to exclude specifically those periods, where the culture is the least competitive in relation to weeds, from the general period of growth and development of a crop. This indicator, based on the scientific publications, has not been portrayed for the oilseed radish.

Many scientific publications on this issue highlight that the establishment of a critical weed period allows the effective planning and implementation of an integrated weed protection system based on the determination of identified crop losses and the establishment of phases and inter–phase vegetation periods with the lowest levels of competition in relation to growing in grain fields vegetation (Rana et al., 2016). The critical period indicator also allows for effective herbicide control in terms of both the appropriateness of using chemical protection and the justification for these measures considering the cost of the harvest (Knezevic et al., 2015).

An important factor in the success of weed control in the crop coenosis is the consideration of the competitiveness of a particular crop in relation to weeds in view of the basic technological solutions for the agrophytocenosis models, such as its density (stocking density and row width). Both factors have been found to influence the intensity of growth processes of both – the crop and weed plants, causing different levels of intensity in quantitative and weight terms of competition between them (Rao, 2000; Zimdahl, 2004, 2018; Booth et al., 2010; Bajwa et al., 2017).

It should be marked that critical period of crop–weed competition (CPWC) has two aspects. First is the duration of time a crop has to be kept weed free after planting so that weeds, which will be emerging later, will not reduce the grain harvest. The second is the duration of time in which weeds emerging with the crop can remain before they begin the interference with crop growth and finally reduce the yield (Rana and Kumar, 2014). It is important to reduce the critical period of the crop–weed competition in order to maximize economic revenues. A critical period is defined as the shortest time spell during the life cycle of a crop when weeding will result in the highest yield of crop or economic returns. The unequal growth between a weed and a crop is a necessary part of creating competitive advantage in favour of a crop. The aim of the unequal growth manipulations should coincide with the rapid growth stages of a crop. Tall growing cultivars cover the soil earlier, therefore, critical period of competition is shorter. Although, a critical period of weed competition is longer for dwarf cultivars. In the case of an upland crop, CPWC is longer because of the slow growth. However, CPWC is shorter for an irrigated crop. In general, one third duration of the crop growth is critical for the weed competition. Considering the importance of developing the efficient technologies and weed control strategies, the aim of tackling the basic aspects of this problem is precisely for agrophytocenoses of oilseeds of different technological patterns, for which this indicator is not marked currently as an urgent task.

The study has been carried out on the research field of Vinnytsia National Agrarian University, namely on the dark gray forest soils – Luvic Greyic Phaeozem soils (for WRB classification). The agrochemical potential of the field corresponds to the general features of this type of soil according to the main agrochemical indicators, and it includes: humus content: 2.02–3.2%, easily hydrolyzed nitrogen 67–92, mobile phosphorus 149–220, exchange potassium 92–126 mg / kg of soil at pH 5.5–6.0. The study of the weed formation in the agrophytocenosis of the Zhuravka oilseed radish is conducted on two radically distant technological variants of its modelling at the seeding rate of 4.0 million pieces / ha of similar seeds of the ordinary row sowing (15 cm) and 0.5 million pieces / ha of similar seeds of the wide–row (30 cm) sowing. The study of both options is held on a non–fertilized background. The sowing period for both variants corresponded to the end of the first – the beginning of the second decade of April.

The hydrothermal parameters of the oilseed radish vegetation period varied, having formed certain typological features of the research years (Figure 4.1).

The conditions of 2013 and especially of 2014 can be referred to the most optimal for the growth processes of the oilseed radish due to the combination of slow rates of increase in average daily temperatures and equal precipitation in the end of May – mid–June, which is phenologically, in the study area, corresponds to the active vegetation, and the rare vegetation coincides with the interphase of the phenological stem–flowering period (BBCH 30–65) (Test Guidelines to conduct tests for the distinctness, uniformity and stability of Fodder Radish (*Raphanus sativus* L. var. *oleiformis* Pers.), 2017).

The conditions of 2015 and 2018 for the period of studies on the ratio of rainfall equality, and the nature of the average daily temperature curve should be attributed to stresful for the physiological and growth processes of the oilseed radish plants. For instance, the precipitation distribution in 2015 was uneven with the total absence during the period of the second decade of May – the second decade of June due to the intense and rapid increase of average daily temperatures during the same period at high amplitude of values. This created a double effect of the overall stress of the environmental factor in the inter–phase start of budding–flowering (BBCH 38–64) with respect to the oilseed radish plants and made it possible to effectively evaluate the studied indicators in the environmental–trait system.

A prolonged atmospheric and soil drought with a slight humidity until the second decade of June was observed for the conditions of 2018 against the background of low average daily temperatures, which, unlike the conditions of 2015, affected the magnitude of the architecture of oil radish plants from the stage of rosette formation and its further stalking (BBCH 19–38). It is for these reasons that the stressful year 2018 is the most illustrative in the assessment of stress.

The years of research 2016 and 2017 by hydrothermal parameters should be attributed to the intermediate ones in the six–year study cycle with a similar dynamic regime of average daily temperatures and uneven atmospheric humidity. In this case, the terms of 2016 are close to a number of years 2013–2014, and the conditions of 2017 – to those of 2015. Thus, the increase in the overall favorable hydrothermal regimes of the oilseed radish in the direction of reducing weather risks should be placed in the following order: 2018–2015–2017–2016–2013–2014.

The critical period of sowing weediness was determined by means of widely used methodological approaches (Knezevic, 2000; Knezevic et al., 2002. Knezevic and Datta, 2015). For this purpose, from the total area of the given technological variant, the accounting squares with an area of each 4 m^2 were repeated four times. In turn, accounting sites were divided into two options. The first one involved the cultivation of the weed–free radish (with their complete removal) sequentially with a period of 15–90 days after sprouting (DAS).

The second was to be keep the sites under analysis in a state of weed abundancy at the same consecutive interval of 15–90 days after sprouting (DAS). Moreover, each square is kept plowed up to a certain reporting moment (15, 30, etc. days after sprouting) and after that it was maintained in a weed–free state until harvesting. This scheme is typical for the study of the critical period of weed control on cross–flowering crops (Hamzei et al., 2007). Afterwards, we gather the crops, the harvest is taken down for every sqaure, the results of each site are compared to the yield of completely weed free one. Observation is focused on the aspects: what the weed free period is, harvest as an increasing significant and at par with treatment of weedy conditions up to a particular period.

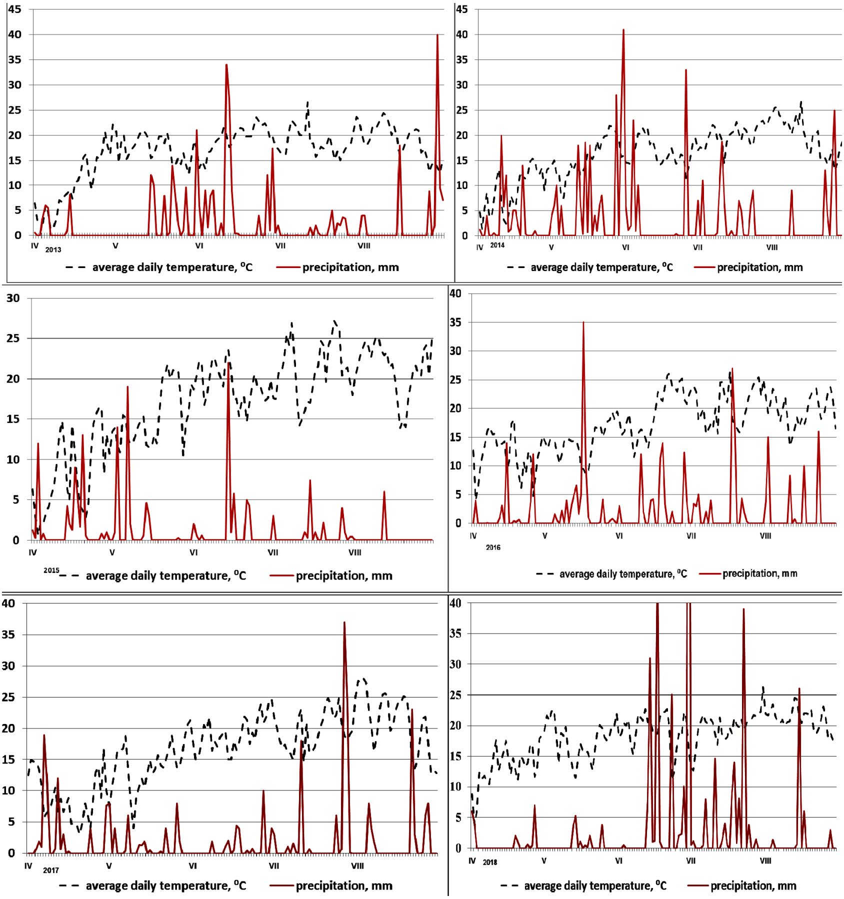


Figure 4.1 – The hydrothermal conditions for April–August (2013–2018) in the consecutive order from left to right and from top to bottom in 2013, 2014, 2015, 2016, 2017, 2018 (Tsytsiura, 2020)

A detailed system of weediness formation peculiarities of the oilseed radish agrophytocenosis is received in various technological ways of the pattern on the green pod phase (BBCH 75–79), on the background without taking a fertilizer or any anti–weed measures, implementing widely–used methodical approaches to recording weeds (Kosolap, 2004; Rana and Kumar, 2014), defining the following indicators (based on the initial recommendations (Curtis and Mclntosh, 1950; Misra, 1968; Dombois and Ellenberg, 1974)):

Density $D = \frac{TNI}{TNQ}$ (4.1)

TNI–Total number of individuals of a species in all squares; TNQ–Total number of squares studied

Frequency $F = \frac{TOI}{TNQ} \cdot 100$ (4.2)

where TOI–Total number of squares in which the species occurred

Abundance $Ab = \frac{TNI}{TOI}$ (4.3)

Relative density $RD = \frac{TNI}{TNS} \cdot 100$ (4.4)

where TNS–Number of individuals of all the species

Relative frequency $RF = \frac{TOI}{TOAS} \cdot 100$ (4.5)

where TOAS–Number of occurrence of all the species

Relative abundance $RAb = \frac{Ab}{TAb} \cdot 100$ (4.6)

where TAb–Total abundance of all species in all squares

Importance Value Index (Curtis, 1959) $IVI = RD + RF + RAb$ (4.7)

Summed dominance ratio $SDR = \frac{IVI}{3}$ (4.8)

The frequency classes of weed species is determined with regard to Raunkiaer (1934). There are five corresponding frequency classes, i.e. 'A' class with the species of frequency ranging from 1–20%; 'B' class 21–40%; 'C' class 41–60%; 'D' class 61–80% and 'E' class 81–100%. Furthermore, compare the weed community frequency patterns with the normal frequency pattern of Raunkiaer (A>B>C>=D<E). Based on the frequency pattern of the community, we determine the homogeneity and heterogeneity of the vegetation. If the values are high with respect to B, C and D, then the community is said to be heterogeneous where higher values of E indicates the homogeneous nature.

The layer of weed formation was determined by Maltsev's method (1962) using the tier criterion K = (H) 1/2 where H is the average quantitative value of weeds in sowing and the interval of weed height relative to the height of cultivated plants (IX). Several types of layers are distinguished according to the specified criteria: a ground layer (I) (K = 0,2; IN = 0–0,1), a lower layer (II) (K = 0,5; IN = 0,1–0,5), a middle layer (III) (K = 0.9; IN = 0.5–1.0), an upper layer (IV) (K = 1.2; IN = 1.0–2.0). Non–tiered plants (V) were attributed to coils and saline weeds, although they were assigned corresponding values by the nature of their altitude development. A generalized estimation of sowing weed (GD) was calculated on the basis of the layering indices:

$$GD = K \cdot D \qquad (4.9)$$

The species composition of the weeds is determined according to the state classifiers–determinants of Ukraine (Barbarich et al., 1970; Veselovsky et al., 1988). Latin weed names are refined according to European naming rules (Williams and Hunyadi, 1988). Weed classification is conducted according to generally accepted criteria for their life expectancy, the developmental cycle, the breeding character, spreading, and the type of a weed (Kosolap, 2004; Rana and Kumar, 2014).

The current study also dwells upon indicators of the environmental plasticity (bi) and environmental stability (Si^2) in relation to the Ab index according to the basic approaches of their calculation (Eberhart and Russel, 1966). Oilseed radish yields were calculated using a standardized methodology for the cruciferous crop group (Saiko, 2011), using experimental statistics approaches (Sokal & Rohlf, 2012) in the form of Multivariate Analysis of Variance (MANOVA) and the statistical application programme package R (Foundation for Statistical Computing Platform version 3.5.3 (2019–03–11)), Statistica, Exel, CurveExpert Pro**:** 2.6.5.

The level of variation of indicators was conducted according to coefficient of variation (CV): very low (CV<7%); low (CV=8–12%); average (CV=13–20%); increased (CV=21–30%); high (CV=31–40%); very high (CV> 40%).

The peculiarities of weed formation of any coenosis should be considered altogether with the features of the growth and development of the main forming crop (Andrew et al., 2015). The oilseed radish has many characteristics in the vegetative development, they include the slow growth rate from the cotyledons phase to the rosette phase (BBCH 8–15), the intense reduction of stemming in the full phase of the green pod (BBCH 71–80), the cessation of any growth processes already at the phenological stage of the yellow–green pod (BBCH 75–85), the tendency to stem's laying out of the coenosis at the main fruiting stages (BBCH 76–85). This nature of the growth processes of oilseed plants causes a high level of threat from the weed growth in the early stages of its vegetation and the intensive weed growth in a slight stalk with a change in the dominance of the general vegetation in the upper layer. In addition, the extended flowering period, which is combined with a long phase of the pod formation and seed ripening against the background of the medium sowing rate, leads to increased dominance of weed plants in the microstage period of the complete yellow and brown ripeness of the pod (BBCH 75–89). Consequently, the cenosis of the oilseed radish (due to the above mentined features) is characterized by oscillation in the vertical dominance of certain biological weed groups. The total number of weed species at the maximum occurrence, found in calculations of different research years, is 48, belonging to 47 genera (Table 4.1).

Table 4.1

The specific generic spectrum of weeds in the agrocenoses of the radish of the oil variety 'Zhuravka' in the system of averaged indicators of technological variants of modelling a cenosis on a phase of a green pod (BBCH 71–77) (on the average for 2013–2018) (Tsytsiura, 2020)

Family	Maximum number of species counted, spieces.	Structure, %	Maximum number of genera reported, pcs.	Structure, %
Asteraceae	9	18.75	7	14.89
Brassicaceae	7	14.58	8	17.02
Poaceae	7	14.58	6	12.77
Boraginaceae	5	10.42	5	10.64
Caryophyllaceae	5	10.42	4	8.51
Fabaceae	4	8.33	6	12.77
Chenopodiaceae	5	10.42	5	10.64
Euphorbiaceae	3	6.25	3	6.38
Lamiaceae	3	6.25	3	6.38
Total	48	100.00	47	100.00

Among the species, the most common families are Asteraceae, Brassicaceae and Poaceae – a total of 50.0% in the overall structure of the ratio. A complex layer structure of the weediness formation of the oilseed radish agrophytocenosis in the context of its main phenological phases was also specified during the long-term evaluations (Table 4.2).

Before the phenological phase of the beginning of stalking (BBCH – 36–52), the lower layer of the oilseed radish agrocenosis is occupied by weeds such as *Elytrigia repens (L.) Gould, Equisetum arvense L., Taraxacum officinale Wigg., Polygonum scabrum Moench, Setaria glauca L., Setaria viridis L., Lamium purpureum L, Thlaspi arvense L., Capsella bursa–pastoris (L.) Medic., Stellaria media L*. There are weeds in the same altitude with the radish oil plants: *Brassica campestris L.*, *Raphanus raphanistrum L.*, *Sinapis arvensis L.*, *Chenopodium album L.*, *Amaranthus retroflexus L.*, *Echinochloa crus–galli L.*, *Galium aparine L.*, *Rocket-cress R. Br.*, *Convolvulus arvensis L.*. The leading role in the coenosis, by the altitude gradient, belong to the weeds such as Sonchus arvensis L, *Cirsium arvense L.*, *Lactuca tataricia L.*, *Artemisia absinthium L.*, *Artemisia vulgaris L.* During the ripening of the oilseed radish plants, the nature of altitude dominance changes in favour of weeds that previously occupied the middle and higher layers in relation to the height of the oilseed radish plants.

This essense of the growth processes stipulates differences in the competitiveness levels of the oilseed radish plants and determines the critical period of its susceptibility to weeds in the interphase of the germination–stalking period (microstages BBCH 10–36). It is determined that the weedy type of the oilseed radish agrocenosis is oscillatory from dicotyledonous–cereal–non–perennial in the interphase period germinate–rosette – to root–germinating–rhizome–non–perennial type in the interphase period of the green–yellow ripeness of pods (BBCH 70–84).

It should be noted that according to the nature of the agrocenosis weed types formation and the magnitude of the frequency index there can be singled out individual species, that correlates to the results of the individual studies It should be noted that according to the nature of the formation of weed types of agrocenosis and the value of the frequency index, bridges of certain species are found, which corresponds to the results of individual studies (Aldrich, 1987; Szumigalki and van Acker, 2005; Page et al., 2010; Afifi and Swanton, 2012; Harris et al., 2015; Zimdahl, 2018), a rare oilseed radish in a system of intensive planting density of standing can be attributed to crops with high competition potential in relation to the main weed species.

The results of assessments of weed vegetation dynamics indicate a gradual increase in cenotic tension due to the gradual transition of dominant weed species such as *Chenopodium album L.*, *Amaranthus retroflexus L.*, *Echinochloa crus–galli L.*, *Elytrigia repens (L.)*, *Sonchus arvensis L.*, *Cirsium arvense L.*, *Convolvulus arvensis L.* in the middle and upper sowing stages while increasing the frequency of their determination by 1.1–1.3 times. The problem of the remarkable dominance of individual weeds, including the multi–year cycle of development, is common in the aspects of the effective weed control over all cross–flowering crops (Hulting, 2004; Lososova et al., 2004; Harris et al., 2015).

As a result, the phenological periodization of weed formation in the agrocenosis of the oilseed radish and the nature of their layer development is confirmed by their basic physiological features considering the maximum dense and minimal dense technological model of the oilseed radish coenosis on the phenological phase of the crop, which corresponds to Table 4.3.

Table 4.2

Typology of weeds dynamics of the oilseed radish agrophytocenosis in the context of the main interphase periods in the context of two technological variants of its modelling (on the average for 2013–2018) (Tsytsiura, 2020)

The interphase period	**Types of weeds growth**	**Weeds layers**	**The main representatives of weeds within each layer and the frequency (F,%) of their determination**
1	2	3	4
BBCH 10–19 (germination– rosette)	Non–perennial (dicotyledonous–cereal–annual)	I (П), II (Н), III (С)	**Groundwater:** *Capsella bursa–pastoris* 8.5* (10.7**)%, *Stellária média* 2.4 (4.2)%, *Thlaspi arvense L.* 7.5* (9,3**)%*, Veronica hederifolia* 2.2 (1.3)%, *Poa annua L.* 0.9 (1.3)%. **Lower:** *Galium aparine L.* 1.3 (1.9)%*, Taraxacum officinale Wigg.* 1,8 (2.4)%*, Equisetum arvense L.)* (2.4 (6.7)%*, Elytrigia repens (L.) Gould* (7.5 (24.7)%*, Sonchus arvensis L* 8.4 (14.2)%, *Convolvulus arvensis L.* 12,4 (20,3)%*, Brassica campestris L.* 1.5 (6.9)%, *Raphanus raphanistrum L.)* 5.5 (6.7)%, *Sinapis arvensis L.* 2.8 (3.3)%, *Carduus acanthoides L.* 0.5 (0.8)%. **Middle:** *Rocket-cress R.Br.* 5.5 (12.8)%, *Lactuca tatarica L*) 10.8 (16.4)%, *Cirsium arvense L.* 11.8 (21.3)%.

(End of Table 4.2)

1	2	3	4
BBCH 20–39 (rosette–stalking)	Non–perennial–root–sprout–rhizome	II–IV(H–B)	**Groundwater:** *Stellária média* 8.7 (6.5)%, *Veronica hederifolia* 6.8 (3.1)%, *Anagallis arvensis L. 6.3 (3.9)%.* **Lower:** *Capsella bursa–pastoris* 10.8 (12.7)%, *Thlaspi arvense L.)* 9.9 (11.8)%, *Artemisia absinthium L.* 1.2 (2.2)%, *Artemisia vulgaris L.* 0.6 (1.3) %*, Chenopodium album L.* 18.5 (27.3)%, *Polygonum scabrum Moench 7.8* (12.6)%, *Amaranthus retroflexus L.* 22.5 (30.3)%, *Echinochloa crus–galli L.*(33.8 (40.2)%, *Setaria glauca L. 37.9 (47.2)%, Setaria viridis L. 2.8* (3.5)%, *Tripleurospermum inodorum (L.) Sch. Bip.* 6.8 (10.1)%. **Middle:** *Galium aparine L.)* 2.2 (3.4)%, *Rocket-cress R. Br.* 9.3 (15.7)%*, Elytrigia repens (L.) Gould* 9.8 (30.6) %*, Sonchus arvensis L.* 12.8 (21.8)%, *Cirsium arvense L.)* 18.1 (25.7)%, *Convolvulus arvensis L.* 19.1 (22.8)%. *Lactuca tataricia L.* 12.6 (20.3)%, *Brassica campestris L.* 3.2 (7.8 %), *Raphanus raphanistrum L. 2*.6 (5.3)%, *Rocket-cress R.Br.* 2.0 (8.7) %, *Poa annua L.* 1.9 (2.8)%, *Sinapis arvensis L.* 2.7 (3.5)%, *Carduus acanthoides L.* 0.9 (1.1)%. **Upper:** *Brassica campestris L.* 6.3 (12.8 %), *Raphanus raphanistrum L. 7.6* (8.1)%, *Rocket-cress R.Br.* 4.6 (13.5) %*, Sinapis arvensis L.* 3.7 (4.9)%
BBCH 50–69 (budding – flowering)	Non–perennial–root–sprout–rhizome	II–IV (H–B)	**Groundwater:** (*Stellária média*) 10.6 (6.9) %, *Veronica hederifolia* 10.8 (4.2)%, *Anagallis arvensis L.* 10.5 (5.2)%*, Portulaca oleraceae L. 10.5 (7,7)%, Elytrigia repens (L.) Gould 5,6* (11.9) %. **Lower:** *Galinsoga parviflora Cav.* 16.8 (30.2)%, *Chenopodium album L.* 10.9 (16.2)%, *Elytrigia repens (L.) Gould* 4.9 (9.7) %, *Echinochloa crus–galli L.*(14.2 (17.5)%, *Setaria glauca L.* 21.6 (31.3)%, *Cynodon dactylon L.* 5.6 (8.3)%, *Lepidium ruderale L.* 4.8 (6.1)%, *Erigeron canadensis L.* 7.4 (9.1)%, *Amaranthus retroflexus L* 16.3 (22.7)%, *Setaria glauca L.)* 23.9 (33.5)%, *Echinochloa crus–galli L.* 16.7 (24.8)%, *Sonchus arvensis L* 10.8 (14.7)%, *Convolvulus arvensis L.* 9.6 (11.8)%, *Poa annua L. 2.4* (3.2)%. **Middle**: *Erigeron canadensis L.* 5.4 (7.5)%, *Chenopodium album L.)* 20.2 (34.5)%, *Polygonum scabrum Moench)* 12.6 (20.8)%, *Amaranthus retroflexus L.)* 24.6 (32,9)%, *Echinochloa crus–galli L.* 16.2 (22.7)%, *Setaria glauca L.* 27.8 (35.6) %*, (Elytrigia repens (L.) Gould* 20.8 (32.3)%*, Sonchus arvensis L* 12.9 (19.1)%, *Cirsium arvense L. 15.9* (22.7) %, *Convolvulus arvensis L.)* 15.2 (20.9) %*, Lactuca tataricia L.* 6.8 (11.4)%, *Artemisia absinthium L.* 1.5 (2.6) %, *Artemisia vulgaris L.* 1.7 (2.5)%*, Tripleurospermum inodorum (L.) Sch. Bip)* (6.4 %) *Carduus acanthoides L.* 1.1 (1.3)%, *Brassica campestris L.* 2.8 (3.7)%, *Raphanus raphanistrum L.* 1.7 (4.1)%, *Rocket-cress R.Br.* 2.8 (5.4) %*, Sinapis arvensis L.* 2.3 (3.4)%. **Upper:** *Chenopodium album L.* 18.9 (24.5)%*, Echinochloa crus–galli L.* 10.8 (15.9)%*, Sonchus arvensis L*) 5.8 (7.2) %, *Cirsium arvense L.* 6.8 (9.3) %, *Convolvulus arvensis L.* 4.2 (5.3)%, *Amaranthus retroflexus L.* 10.7 (12.2)%, *Artemisia absinthium L.* 1.8 (2.2)%, *Artemisia absinthium L.* 1.4 (1.7)%, *Carduus acanthoides L.* 1.2 (1.6)%

* – for the technological variant 4,0 million pieces/ha of similar seeds; ** – for the technological variant 0.5 million pieces / ha of similar seeds.

Table 4.3

The phytosociological attributes of oilseed radish weeds on average for the period 2013–2018 per a starting fruiting phase (OVS 70–74) (for the total annual number of accounted squares of 1m² 50) (Tsytsiura, 2020)

Name of the species		TOI. шт	CV_{TOI}. %	TNI. шт	CV_{TIN}. %	Ab	D	F. %	Fcl	RAb. %	RD. %	RF. %	IVI. %	SDR. %	K
Thlaspi arvense L	*1**	3.83	19.6	5.17	22.6	1.35	0.10	7.67	A	1.30	0.44	1.01	2.75	0.92	0.5
	2	10.50	23.1	12.33	16.7	1.17	0.25	21.00	B	0.89	0.60	2.19	3.68	1.23	0.5
Linaria vulgaris Milk	*1*	2.33	22.1	2.17	18.8	0.93	0.04	4.67	A	0.90	0.18	0.62	1.69	0.56	0.9
	2	3.50	53.5	3.50	53.5	1.00	0.07	7.00	A	0.75	0.17	0.73	1.65	0.55	0.9
Xanthoxalis fontana	*1*	1.33	38.7	2.17	34.7	1.63	0.04	2.67	A	1.57	0.18	0.35	2.10	0.70	0.2
	2	4.33	43.0	5.83	51.3	1.35	0.12	8.67	A	1.02	0.29	0.90	2.20	0.73	0.2
Barbarea vulgaris R.Br.	*1*	3.33	15.5	4.33	27.9	1.30	0.09	6.67	A	1.25	0.37	0.88	2.50	0.83	0.9
	2	11.33	20.6	16.67	47.3	1.47	0.33	22.67	B	1.11	0.81	2.36	4.28	1.43	0.9
Daucus carota L.	*1*	1.83	22.3	2.50	21.9	1.36	0.05	3.67	A	1.32	0.21	0.48	2.01	0.67	0.5
	2	3.67	44.5	5.33	64.6	1.45	0.11	7.33	A	1.10	0.26	0.76	2.12	0.71	0.5
Lappula squarrosa (Retz.) Dumort	*1*	1.33	38.7	3.17	23.8	2.38	0.06	2.67	A	2.29	0.27	0.35	2.91	0.97	0.9
	2	1.83	41.1	2.83	56.5	1.55	0.06	3.67	A	1.17	0.14	0.38	1.69	0.56	0.9
Lamium purpureum L	*1*	3.00	21.1	4.67	17.5	1.56	0.09	6.00	A	1.50	0.39	0.79	2.69	0.90	0.2
	2	2.50	55.1	5.17	62.9	2.07	0.10	5.00	A	1.56	0.25	0.52	2.33	0.78	0.2
Berteroa incana L.	*1*	1.17	35.0	2.17	18.8	1.86	0.04	2.33	A	1.79	0.18	0.31	2.28	0.76	0.5
	2	1.50	36.5	3.33	41.0	2.22	0.07	3.00	A	1.68	0.16	0.31	2.15	0.72	0.5
Veronica hederifolia L.	*1*	6.00	14.9	11.00	14.1	1.83	0.22	12.00	A	1.77	0.93	1.58	4.28	1.43	0.2
	2	2.33	22.1	4.83	49.7	2.07	0.10	4.67	A	1.56	0.24	0.49	2.28	0.76	0.2
Carduus acanthoides L.	*1*	3.33	15.5	5.33	28.2	1.60	0.11	6.67	A	1.54	0.45	0.88	2.87	0.96	1.2
	2	4.17	28.1	19.17	32.2	4.60	0.38	8.33	B	3.47	0.94	0.87	5.27	1.76	1.2
Lepidium ruderale L.	*1*	2.33	22.1	3.83	19.6	1.64	0.08	4.67	A	1.59	0.32	0.62	2.53	0.84	0.5
	2	4.33	34.7	11.33	21.4	2.62	0.23	8.67	A	1.97	0.55	0.90	3.43	1.14	0.5

(End of Table 4.3)

Erigeron	1	5.67	18.2	10.33	11.7	1.82	0.21	11.33	A	1.76	0.87	1.50	4.13	1.38	0.9
canadensis L.	2	9.67	16.9	24.00	32.6	2.48	0.48	19.33	A	1.87	1.17	2.01	5.06	1.69	0.5
Raphanus	1	4.17	18.1	6.33	19.1	1.52	0.13	8.33	A	1.47	0.53	1.10	3.10	1.03	0.9
raphanistrum L.	2	4.17	18.1	10.67	29.4	2.56	0.21	8.33	A	1.93	0.52	0.87	3.32	1.11	0.9
Amaranthus	1	2.33	22.1	3.33	31.0	1.43	0.07	4.67	A	1.38	0.28	0.62	2.28	0.76	0.9
Blifoides S. Wats.	2	2.17	34.7	2.33	51.9	1.08	0.05	4.33	A	0.81	0.11	0.45	1.38	0.46	0.5
Anagallis	1	6.33	12.9	8.33	14.5	1.32	0.17	12.67	A	1.27	0.70	1.67	3.65	1.22	0.2
arvensis L.	2	3.00	29.8	5.17	41.4	1.72	0.10	6.00	A	1.30	0.25	0.63	2.18	0.73	0.2
Brassica	1	11.17	18.3	19.17	14.2	1.72	0.38	22.33	B	1.66	1.62	2.95	6.22	2.07	0.9
campestris L.	2	9.67	22.3	14.17	30.7	1.47	0.28	19.33	A	1.11	0.69	2.01	3.81	1.27	0.9
Artemisia	1	3.33	24.5	4.33	27.9	1.30	0.09	6.67	A	1.25	0.37	0.88	2.50	0.83	1.2
vulgaris L	2	2.83	34.7	7.83	14.9	2.76	0.16	5.67	A	2.08	0.38	0.59	3.06	1.02	0.9
Artemisia	1	2.33	22.1	5.33	19.4	2.29	0.11	4.67	A	2.21	0.45	0.62	3.27	1.09	1.2
absinthium L..	2	2.17	34.7	3.50	30.0	1.62	0.07	4.33	A	1.22	0.17	0.45	1.84	0.61	1.2
Taraxacum	1	5.00	21.9	8.33	25.9	1.67	0.17	10.00	A	1.61	0.70	1.32	3.63	1.21	0.5
officinale	2	11.83	19.6	15.50	24.7	1.31	0.31	23.67	B	0.99	0.76	2.47	4.21	1.40	0.5
Cirsium	1	21.33	23.1	114.50	18.6	5.37	2.29	42.67	C	5.18	9.67	5.63	20.48	6.83	1.2
arvense L.	2	23.83	13.4	149.00	30.6	6.25	2.98	47.67	C	4.71	7.29	4.97	16.96	5.65	1.2
Sonchus	1	14.17	18.1	22.33	17.6	1.58	0.45	28.33	B	1.52	1.89	3.74	7.15	2.38	1.2
arvensis L.	2	17.83	16.0	27.83	28.3	1.56	0.56	35.67	B	1.18	1.36	3.72	6.25	2.08	1.2
Convolvulus	1	9.17	23.3	14.00	12.8	1.53	0.28	18.33	A	1.47	1.18	2.42	5.08	1.69	0.9
arvensis L.	2	12.33	19.0	32.00	26.0	2.59	0.64	24.67	B	1.96	1.56	2.57	6.09	2.03	0.9
Equisetum	1	2.17	18.8	6.00	23.6	2.77	0.12	4.33	A	2.67	0.51	0.57	3.75	1.25	0.5
arvense L.	2	6.17	19.0	14.83	13.1	2.41	0.30	12.33	A	1.81	0.73	1.28	3.82	1.27	0.5
Cynodon	1	5.17	22.6	11.33	15.5	2.19	0.23	10.33	A	2.12	0.96	1.36	4.44	1.48	0.5
dactylon L.	2	6.67	27.9	14.83	16.2	2.23	0.30	13.33	A	1.68	0.73	1.39	3.79	1.26	0.5
Achillea	1	2.33	22.1	4.17	28.1	1.79	0.08	4.67	A	1.72	0.35	0.62	2.69	0.90	0.9
millefolium L.	2	5.17	22.6	9.50	14.5	1.84	0.19	10.33	A	1.39	0.46	1.08	2.93	0.98	0.9

(End of Table 4.3)

Elytrigia repens L	*1*	27.33	25.6	70.17	19.4	2.57	1.40	54.67	C	2.48	5.92	7.22	15.62	5.21	0.9
	2	35.83	15.4	130.00	19.8	3.63	2.60	71.67	D	2.74	6.36	7.47	16.56	5.52	0.9
Delphinium consolida	*1*	6.50	23.3	10.33	22.6	1.59	0.21	13.00	A	1.53	0.87	1.72	4.12	1.37	0.5
	2	7.83	26.1	13.67	15.8	1.74	0.27	15.67	A	1.32	0.67	1.63	3.62	1.21	0.5
Tripleuro-spermum inodorum L.	*1*	8.17	32.3	15.17	13.5	1.86	0.30	16.33	A	1.79	1.28	2.16	5.23	1.74	0.5
	2	21.33	10.1	41.17	24.3	1.93	0.82	42.67	C	1.46	2.01	4.44	7.91	2.64	0.5
Senecio vernalis Waldst	*1*	5.50	25.1	7.33	23.9	1.33	0.15	11.00	A	1.29	0.62	1.45	3.36	1.12	0.9
	2	8.83	16.7	13.83	16.7	1.57	0.28	17.67	A	1.18	0.68	1.84	3.70	1.23	0.9
Lactuca Tatarica L.	*1*	5.33	22.7	6.33	35.5	1.19	0.13	10.67	A	1.15	0.53	1.41	3.09	1.03	0.9
	2	10.83	20.6	22.50	24.5	2.08	0.45	21.67	B	1.57	1.10	2.26	4.92	1.64	0.9
Capsella bursa pastoris L.	*1*	10.33	22.6	14.00	20.2	1.35	0.28	20.67	A	1.31	1.18	2.73	5.22	1.74	0.2
	2	10.00	16.7	23.83	13.4	2.38	0.48	20.00	A	1.80	1.17	2.08	5.05	1.68	0.2
Centaurea cyanus L.	*1*	5.50	15.2	7.33	22.3	1.33	0.15	11.00	A	1.29	0.62	1.45	3.36	1.12	0.5
	2	5.33	19.4	7.67	13.5	1.44	0.15	10.67	A	1.08	0.37	1.11	2.57	0.86	0.5
Portulaca oleraceae L.	*1*	8.33	28.1	16.00	17.7	1.92	0.32	16.67	A	1.85	1.35	2.20	5.40	1.80	0.2
	2	6.00	14.9	13.50	15.4	2.25	0.27	12.00	A	1.70	0.66	1.25	3.61	1.20	0.2
Galinsoga parviflora Cav.	*1*	12.50	17.3	16.33	21.1	1.31	0.33	25.00	B	1.26	1.38	3.30	5.94	1.98	0.5
	2	23.17	13.8	46.50	24.2	2.01	0.93	46.33	C	1.51	2.27	4.83	8.61	2.87	0.5
Spergula vulgaris Boenn.	*1*	2.50	21.9	5.33	28.2	2.13	0.11	5.00	A	2.06	0.45	0.66	3.17	1.06	0.5
	2	2.33	22.1	4.67	26.0	2.00	0.09	4.67	A	1.51	0.23	0.49	2.22	0.74	0.5
Amaranthus retroflexus L.	*1*	31.17	16.5	75.17	22.4	2.41	1.50	62.33	D	2.33	6.35	8.23	16.90	5.63	1.2
	2	35.83	13.5	156.00	18.3	4.35	3.12	71.67	D	3.28	7.63	7.47	18.38	6.13	0.9
Polygonum aviculare L.	*1*	1.50	36.5	2.33	22.1	1.56	0.05	3.00	A	1.50	0.20	0.40	2.09	0.70	0.2
	2	2.33	22.1	5.00	17.9	2.14	0.10	4.67	A	1.62	0.24	0.49	2.35	0.78	0.2
Sonchus oleraceus L.	*1*	5.50	19.1	8.17	16.3	1.48	0.16	11.00	A	1.43	0.69	1.45	3.57	1.19	1.2
	2	8.17	19.6	10.50	13.1	1.29	0.21	16.33	A	0.97	0.51	1.70	3.18	1.06	1.2

(End of Table 4.3)

Polygonum scabrum Moench.	*1*	12.33	18.3	21.00	12.0	1.70	0.42	24.67	B	1.64	1.77	3.26	6.67	2.22	0.5
	2	17.17	15.8	44.00	20.9	2.56	0.88	34.33	B	1.93	2.15	3.58	7.66	2.55	0.5
Echinochloa crus–galli L.	*1*	29.33	22.4	77.83	16.6	2.65	1.56	58.67	C	2.56	6.57	7.74	16.88	5.63	1.2
	2	35.83	13.3	97.67	18.5	2.73	1.95	71.67	D	2.06	4.78	7.47	14.30	4.77	1.2
Setaria viridis L.	*1*	12.50	24.7	34.17	16.4	2.73	0.68	25.00	B	2.64	2.88	3.30	8.82	2.94	0.5
	2	8.33	22.3	19.50	22.6	2.34	0.39	16.67	A	1.76	0.95	1.74	4.45	1.48	0.5
Setaria glauca L..	*1*	28.00	19.6	267.83	18.1	9.57	5.36	56.00	C	9.23	22.61	7.39	39.24	13.08	0.9
	2	31.17	15.2	690.17	18.6	22.14	13.80	62.33	D	16.70	33.75	6.49	56.94	18.98	0.5
Galium aparine L.	*1*	5.33	25.6	7.83	27.3	1.47	0.16	10.67	A	1.42	0.66	1.41	3.49	1.16	0.5
	2	2.50	21.9	6.00	21.1	2.40	0.12	5.00	A	1.81	0.29	0.52	2.62	0.87	0.5
Chenopodium album L.	*1*	21.33	16.7	205.33	14.7	9.63	4.11	42.67	C	9.29	17.34	5.63	32.26	10.75	1.2
	2	27.00	11.2	243.50	18.7	9.02	4.87	54.00	C	6.80	11.91	5.63	24.33	8.11	0.9
Sinapis arvensis L.	*1*	4.33	23.8	8.00	23.7	1.85	0.16	8.67	A	1.78	0.68	1.14	3.60	1.20	0.9
	2	4.00	22.4	19.33	21.1	4.83	0.39	8.00	A	3.64	0.95	0.83	5.42	1.81	0.9
Polygonum convolvulus L.	*1*	2.50	21.9	6.33	12.9	2.53	0.13	5.00	A	2.44	0.53	0.66	3.64	1.21	0.9
	2	2.33	22.1	1.83	41.1	0.79	0.04	4.67	A	0.59	0.09	0.49	1.17	0.39	0.9
Poa annua L..	*1*	2.33	22.1	3.33	15.5	1.43	0.07	4.67	A	1.38	0.28	0.62	2.28	0.76	0.5
	2	2.33	22.1	2.00	44.7	0.86	0.04	4.67	A	0.65	0.10	0.49	1.23	0.41	0.5
Stellaria media L.	*1*	6.17	19.0	14.33	10.5	2.32	0.29	12.33	A	2.24	1.21	1.63	5.08	1.69	0.2
	2	4.00	27.4	10.83	21.4	2.71	0.22	8.00	A	2.04	0.53	0.83	3.41	1.14	0.2
Всього	*1*	378.8	22.3*	1184.3	20.4*	103.6	23.7	757.7	–	100.0	100.0	100.0	300.0	100.0	33.9
	2	480.0	24.1*	2045.2	28.6*	132.6	40.9	960.0	–	100.0	100.0	100.0	300.0	100.0	31.8

TOI = Total Occurrence of Individuals, CV_{TOI} = coefficient of variation of the Total Occurrence of Individuals, TNI = Total Number of Individuals, CV_{TNI} = coefficient of variation of the Total Number of Individuals, Ab = Abundance, D = Density, F = Frequency, Fcl = Frequency classes; RA= Relative Abundance, RD = Relative Density, RF = Relative Frequency, IVI = Importance Value Index, and SDI = Summed dominance ratio, K=tier criterion; 1 – for seeding rates of 4.0 million pieces / ha of similar seeds; 2 sowing rates of 0.5 million pieces / ha of similar seeds; *– inferior to the value of the flow.

The weed population in the agrophytocenosis of the oilseed radish of two radically remote technological variants is heterogeneous according to the given indicators. This is showed by the ratio of the frequency classes (F) A> B> C> = D <E (Raunkiaer, 1934). To be more specific, the presented indicators determine the amount of dominance in the crop, and the highest indicator is observed among such weed species as *Chenopodium album L.*, *Amaranthus retroflexus L.*, *Echinochloa crus–galli L.*, *Setaria glauca L.*, *Galinsoga parviflora Cav*. До зимуючих однорічників *Lactuca serriola L*, *Galium aparine L.*, *Rocket-cress R. Br.*, *Thlaspi arvense L.*, *Capsella bursa–pastoris (L.) Medic.*, *Tripleurospermum inodorum (L.) Sch. Bip.* і *Stellaria media L.* The marked spectrum of perennial weeds is represented in the agrocenoses of oilseed radish by the rhizome forms of *Elytrigia repens L.*, *Equisetum arvense L.*, root–sprout forms of *Sonchus arvensis L.*, *Cirsium arvense L., Convolvulus arvensis L.*, taproot forks and non–root forms *Taraxacum officinale Wigg.*, *Lactuca tataricia*, *Artemisia absinthium L.*, *Artemisia vulgaris L.* Contrary to the revealed peculiarities for a spring rapeseed (Martin et al., 2001), a white mustard (Singh, 2006), more distinctive layer differentiation of weed species is typical of the agrocenosis of the oilseed radish and strongly marked inhibition of the soil and the lower layer, especially interfacial stalking–flowering period (BBCH 25–55).

It should be noted that both quantitative and structured weed abundances in the coenosis of oilseed radish with a density of 4.0 million pieces / ha of similar seeds are substantially lower than in the version of 0.5 million pieces / ha of similar seeds. Therefore, the total weed abundance in the first variant over the study period equals 17.2 ppm less than in the second variant of the coenosis density. With the preservation of the species structure of weeds, the layering level of their formation was less than 2.1 pieces of the displaced dominant by the level coefficient (K) in the variant of 0.5 million pieces / ha of similar seeds, which indicates the increase in the vitality of the oil–radish plants for reduction in seeding rates on the one hand, and on the other, an overall increase in F of 26.7% in this embodiment indicates an overall increase in the number of weeds in the lower and middle layers. That is to say, the effect of competitiveness of weed plants in relation to weeds tends to decline as the density of their plants is reduced, but this decrease is not directly proportional, since it is limited by the redistribution of the layering structure of the weeds and the change in the vitality tactics of the oilseed radish proper. It should also be specified that within the variation in the TII and TNI indices, the number of specific weed species depended on the hydrothermal conditions of the year, since in this case the coefficient of variation determines the annual fluctuations in the number of the definite individual species. Diffrent types of weeds have different degrees of adaptаишдшен to the changing hydrothermal vegetation conditions by the magnitude of the variation coefficient from low to very high. At the same time, the variation in the number of annual plants is on average 5.6% higher than the variation in the number of perennial forms. The variability of the species composition of the weeds is 1.4 times higher than the sowing rate of 0.5 million pieces / ha of similar seeds according to the results of the average value of the variation coefficient in the TNI expression. This confirms our findings once more as to the expansion of the range of vitality tactics of weed species in the oilseed radish agrocenosis by reducing the total cenotic pressure per a unit area. The same is also proved by the Generalized Weed Estimation (GD) score for two coenosis constructs in general. This indicator averaged 22.13 pieces m^{-2} in the layers for the study period for the variant of 4.0 million pieces ha^{-1} of similar seeds, and the option of 0.5 million pieces ha^{-1} of similar seeds embraced 29.79 units / m^2 in layers. This is the proof of a denser spatial orientation of the weed plants on the attenated norms of seeding of the oilseed radish and a more complete filling of the free layering niches with the vegetative parts of the weeds themselves. Such features correspond to certain general laws of phytocenology (Mirkin, 1985) and such indicators as consideration of weed vitality in determining the critical state in weediness of the agrocenosis of the respective crop (Kandasamy, 1997; Monaco et al., 2002; Rao, 2017).

Identifying the relevant indicators of the stability of weed formation in the agrocenosis of the oilseed radish is also important. As it has been specified before, the weather conditions varied during different years of the study, which allowed us to put them in order of favourability to ensure the growth processes of the oil radish. A similar dynamics in the favourability of growth processes is also found for weed plants. The years of assessment have the following indices for the index Abundance (Ab) 2018 (–0.09) –2015 (–0.26) –2017 (–0.05) –2016 (0.21) – 2013 (0.26) –2014 (0.32) according to the methodology for assessing the stability and ductility of indicators (Eberhart and Russel, 1966).

The evaluation of the environmental plasticity (bi) and the environmental stability (Si^2) for the two technological options for modelling the oilseed radish cenosis is showed in Table 4.4 It is known that these indices are divided into the following grouping ranks according to their value (Tai, 1971): I the indicators bi <1, Si2> 0 – have better results in the unfavourable conditions, unstable; II indicators bi <1, $Si^2 = 0$ – have better results in unfavorable conditions, stable; III indicators bi = 1, $Si^2 = 0$ – responds well to the improvement of conditions, stable; IV indicators bi = 1, $Si^2 > 0$ – responds well to the improvement of conditions, unstable; V indicators bi> 1, $Si^2 = 0$ – have better results in favourable conditions, stable; VI indicators bi> 1, $Si^2 > 0$ – have the best results in the favourable conditions.

The obtained results enable us to make many important conclusions. First, dominance among the weed species considered by the correlation bi/Si^2 of the I and VI rank groups indicates a clear differentiation of the weed species by resistance to unfavourable conditions. Species with rank I, which show higher abundance in unfavorable conditions, but with the unstable variant of reaction to the specified conditions, have been estimated as 26 (54.2%, of the total number of the considered species) for the first technological variant of modelling of oilseed radish agrocenosis. Species with the VI rank that respond positively to favourable weather conditions for the first variant are marked as 5 (31.3%). The marginal species of other groups include 7 (14.5%). In the case of changes in the planting density of the oilseed radish, this factor is a regularity in the system of the plasticity assessment and stability of the definite weed species, 27 species (56.3%) are assigned to the first rank, 19 (39.6%) – to rank sixth at the presence of two marginal species in the rank group (4.1%). These results confirm the fact that the competitive potential of weeds in the composition of oilseed agrocenosis in terms of the hydrothermal vegetation conditions is high, and the change of the rank from I to VI in some species for reducing the standing density of oilseed plants is a manifestation of its competitive potential as to the segetal vegetation, which complies with the concept of plasticity (Eberhart and Russel, 1966).

It is necessary to highlight that weeds of the VI rank of the grouping should be attributed to species with numbers to increase significantly when improving both edaphic conditions and the introduction of additional elements in the cultivation technology, namely the use of mineral fertilizers, the increase in feeding areas of cultivated plants and others. This is the case for the oilseed species that are dominant in the coenosis of the radish, such as *Cirsium arvense L., Elytrigia repens L., Galinsoga parviflora Cav., Amaranthus retroflexus L., Echinochloa crus–galli L., Setaria glauca L, Chenopodium album L., Erigeron canadensis L., Carduus acanthoides L.*

As a result, we have scrutinized the peculiarities of weed formation in the agrophytocenosis of the oilseed radish with different technological variants, admitting of shifting the indicator of the critical weed control period (CPWC) (Figure 4.2).

Table 4.4

Ecological plasticity (bi) and ecological stability (Si^2) of Ab indicator under different technological variants of oilseed radish growing at the beginning of the fruiting phase (BBCH 70–74), 2013–2018 (Tsytsiura, 2020)

Name of the species	Variant of constructing agrocenosis of oilseed radish					
	4.0 million pcs./ha of similar seeds			0.5 million pcs./ha of similar seeds		
	bi	Si^2	Ранг	bi	Si^2	Ранг
1	2	3	4	5	6	7
Thlaspi arvense L.	–0,87	0,09	I	–0,56	0,02	I
Linaria vulgaris Milk.	0,60	0,11	I	0,01	0,00	II
Xanthoxalis fontana	6,03	0,17	VI	–0,08	0,12	I
Rocket-cress R.Br.	0,69	0,11	I	0,87	0,20	I
Daucus carota L.	–3,16	0,08	I	1,17	0,03	VI
Lappula squarrosa (Retz.) Dumort	4,58	1,01	VI	1,16	1,10	VI
Lamium purpureum L.	–1,46	0,05	I	2,31	0,12	VI
Berteroa incana L.	–3,05	0,52	I	0,98	0,72	I
Veronica hederifolia L.	1,76	0,08	VI	2,73	0,47	VI
Carduus acanthoides L.	–1,08	0,06	I	2,30	0,18	VI
Lepidium ruderale L.	1,70	0,43	VI	–0,09	0,37	I
Erigeron canadensis L.	–2,20	0,14	I	1,69	0,05	VI
Raphanus raphanistrum L.	0,10	0,01	II	0,60	0,09	I
Amaranthus Blifoides S. Wats.	2,25	0,10	I	–2,82	1,10	I
Anagallis arvensis L.	–0,21	0,01	II	0,71	0,48	I
Brassica campestris L.	–1,01	0,01	II	0,15	0,03	I

(End of Table 4.4)

1	2	3	4	5	6	7
Artemisia vulgaris L.	–2,74	0,17	I	0,35	0,79	I
Artemisia absinthium L.	1,01	0,07	IV	–0,76	0,20	I
Taraxacum officinale	–1,08	0,15	I	0,03	0,04	I
Cirsium arvense L.	5,51	0,20	VI	5,61	0,56	VI
Sonchus arvensis L.	0,03	0,07	I	1,00	0,03	IV
Convolvulus arvensis L.	–0,52	0,16	I	0,55	0,10	I
Equisetum arvense L.	4,08	1,00	VI	–0,18	0,32	I
Cynodon dactylon L.	–0,35	0,04	I	–0,62	0,15	I
Achillea millefolium L.	1,14	0,05	VI	–0,61	0,06	I
Elytrigia repens L.	0,66	0,06	I	1,33	0,09	VI
Delphinium consolida, Consolida regalis	–0,36	0,03	I	0,06	0,22	I
Tripleurospermum inodorum L.	3,05	0,70	VI	1,77	0,17	VI
Senecio vernalis Waldst	3,34	0,01	V	–0,16	0,21	I
Lactuca tatarica L.	–0,93	0,04	I	0,66	0,01	I
Capsella bursa pastoris L.	2,42	0,14	VI	0,52	0,09	I
Centaurea cyanus L.	2,89	0,21	VI	–0,31	0,07	I
Portulaca oleraceae L.	2,56	0,10	VI	0,18	0,04	I
Galinsoga parviflora Cav.	0,35	0,00	II	1,49	0,00	VI
Spergula vulgaris Boenn.	–1,00	0,62	I	0,59	0,16	I
Amaranthus retroflexus L.	–0,39	0,04	I	1,62	0,20	VI
Polygonum aviculare L.	1,07	0,72	VI	0,48	0,35	I
Sonchus oleraceus L.	0,36	0,01	II	–0,85	0,01	I
Polygonum scabrum Moench.	0,73	0,04	I	1,37	0,03	VI
Echinochloa crus–galli L.	–0,20	0,08	I	1,48	0,10	VI
Setaria viridis L.	0,21	0,09	I	0,49	0,45	I
Setaria glauca L.	11,22	0,63	VI	6,30	0,23	VI
Galium aparine L.	–0,19	0,08	I	0,23	0,29	I
Chenopodium album L.	7,71	0,48	VI	5,35	1,19	VI
Sinapis arvensis L.	0,55	0,10	I	4,34	0,98	VI
Polygonum convolvulus L.	–1,54	0,21	I	1,47	0,12	VI
Poa annua L.	1,15	0,07	VI	1,99	0,08	VI
Stellaria media L.	0,33	0,11	I	1,29	0,56	VI
Parameters Year conditions: F_f 1960,2 ($F_{0.5}$ 2,46); Ab F_f 425,5 ($F_{0.5}$ 1,82); Ab x year conditions F_f 96,3 ($F_{0.5}$ 1,48)						

We have applied the duration of the post–emergence period in the system for determining this indicator, although as observed (Beckie et al., 2008; Rana, 2016), the format of the post–emergence study of weed competition under early spring sowing is more relevant. The use of classical approaches to determining the CPWC (Knezevic et al., 2002; Norsworthy et al., 2004;

Knezevic and Datta, 2015), 5% in particular and 10% of the rate of decline. For the variant of forming the oilseed radish agrocenosis with a seeding rate of 4.0 million pieces ha^{-1} of similar seeds, the rate of 5% reduction of the average crop during the study period was in the range of 5–45 DAS, 10% of the crop loss rate was in the range of 12–40 DAS. For the technological variant of 0.5 million pieces ha^{-1} of similar seeds, the indicated yield reduction levels varied between 6–60 DAS and 13–50 DAS respectively. The interval itself differs from similar indicators for oilseeds close to the radish: a spring and winter rapeseed, a white mustard in particular. On the whole, the total critical period is revealed for a rape, which includes 5 and 10% crop reduction levels, the critical period is specified in the range from 15–40 DAS (Rana and Kumar, 2014) to 15–60 DAS (Beckie et al., 2008; Lemerle et al., 2010). Consequently, the oilseed radish has identical features in terms of the competitiveness to the main weeds. However, our studies have shown a number of differences. The first of these, already mentioned by us, is related to the peculiarities of the oilseed radish plant growth – these are the slow growth rates to the rosette phase of the beginning of stalking (BBW 10–30), and intensive rapid growth rates from the stem stage to the flowering one (BBW 31–50). The level of competition of weed radish plants in relation to weeds increases from the rosette stage and reaches its maximum value within budding due to these peculiarities (OVS 42–50). With the increase in the density of agrocenosis, and for the radish of oilseed in the study area, this is the maximum applied technological option, in addition to increasing the overall competitiveness of the plants in relation to weeds due to the correspondingly higher cover (Mirkin, 1985), also increased internal competition between the cultivated plants of the oilseed radish. In this case, the critical interval between 5 and 10% yield reduction levels is rstricted to 5–7 DAS instead of 9–10 DAS in the variant of 0.5 million pieces/ha of similar seeds. For this reason, the CPWC period for the first technological variant is shortened, and the intersection point of the Gompertz curve and logistics for the first variant was 24 DAS, and for the second – 33 DAS. These features have been found in other several cultures and generalized by a number of researchers (Martin et al., 2001; Zimdahl, 2004; Hamzei et al., 2007; Dobrzański and Adamczewski, 2009; Swanton et al., 2015; Rana, 2016).

Figure 4.2 – Weed invasion in two sectors (A and B) of an oilseed radish field at full maturity in our University field in 2020). (A – weed density m^{-2} – 26; B – weed density m^{-2} – 41) (Tsytsiura, 2020)

Another peculiarity of the oilseed radish is related to the nature of seed yield formation in relation to the formation of the total leafy biomass. By increasing the seeding rate to the critical maximum limit, a general decrease in the reproductive and increase of the vegetative plant architectonics is observed. For this reason, a complex proportion of the crop decline is formed both due to weeds and due to the unique features of the depressing influence of the intraspecific competition.

The opposite processes occur to the variant of critically low seeding rates. As a result, the growth curve (Gompertz Relation) has lower approximation values (R^2) than the logistic curve. A lot of publications highlight these observations as for the evaluation of CPWC period curves (Ahmadvand et al., 2009; Knezevic and Datta, 2015; Zimdahl, 2018).

In addition, due to the higher level of weediness and the decrease in the overall competitiveness of sowing by reducing the potential project surface coverage of the soil surface by one plant (Mirkin, 1985), the relevance of weed control extends to later phenological phases in the development of the oilseed radish plants than for the variant of denser coenoses of a crop.

The determined CPWC shows that herbicides should be applied for the effective herbicide control over the oilseed radish agrocoenosis in the period from germination to the beginning of rosette formation

(BBCH 4–12) at high technological density of the coenosis, and in the period from the beginning of rosette formation to the beginning of stalking (BBCH 10–20) in the variants of extremely low density values. This complies with the conventional weed control strategy (Anderson, 2007; Sanyal, 2008; Harker and O'Donovan, 2013; Andrew et al., 2015; Jugulam et al., 2019).

The heterogeneous qualitiy of weed formation has been determined for agrophytocenoses of the oilseed radish. The overall species diversity is represented by 48 species that constitute four consecutive layers within the height of the oil radish stalk. The nature of the weediness types changes one after another in the light of major stages of the growing season. The prevailing type of weediness in terms of the structure is non–perennial–rooting–sprouting–rhizome. The dominant forms with a higher level of competitiveness as for the oilseed radish plants are represented by cereals of the early and late spring groups (SDR = 22.4 overall for 4.0 million pieces ha^{-1} of similar seeds and 25.6 for 0.5 million pieces ha^{-1} of similar seeds as well as the perennial rhizome forms (SDR 5.2 and 5.5 correspondinly). The dominant role among the broad–leaved (dicotyledonous) weeds is played by the representatives of the late spring group (SDR 24.1 and 24.4 correspondinly) and the perennial rootstock group (SDR 12.6 and 11.8 correspondinly). The attributed features of weeds reported in the agrocenosis of the oilseed radish of different densities were 39.2% by species identity average representation for the technological variant of 0.5 million pieces/ha of similar seeds.

In general, the prevailing weed types belonged to groups I and VI according to the parameters of the ecological plasticity (bi) and ecological stability (Si^2) of the parameter Ab. CPWC depended on the technological density of the oilseed radish agrocenosis, and at its value for the level of 5% reduction in the yield of 4.0 million pieces ha^{-1} of similar seeds was 5–45 DAS, which was 14 DAS less than in the version 0.5 mn pieces ha^{-1} of similar seeds. This indicator was also lower for the denser study of the oilseed radish agrocenosis by 9 DAS for the level of 10% reduction in harvest. The most appropriate period of using herbicides for the effective control over their number, taking into account the criterion CPWC for the full range of technological parameters of forming the agrocenosis of oilseed radish, corresponds to the period of seedling – the start of sprouting (BBCH 4–20).

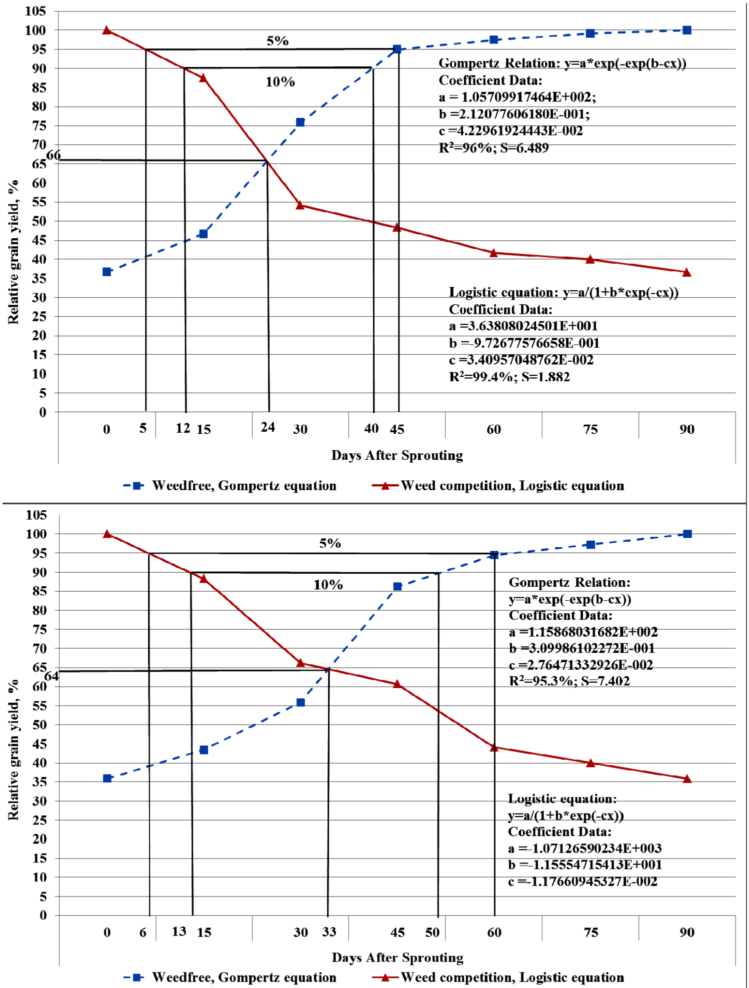


Figure 4.3 – The critical period of the weed competition of the oilseed radish agrophytocenosis with different seeding technological model (the top position for seeding rates of 4.0 million pieces ha^{-1} of similar seeds, bottom position – for seeding rates of 0.5 million pieces ha^{-1} of similar seeds), 2013–2018 average (determination of graph parameters in CurveExpert Pro: 2.6.5) (Tsytsiura, 2020)

Any agrophytocenosis of cultivated plants can be visualized as a complex system consisting of 1–2 species of cultivated plants and a multispecies complex of weeds. The efficiency of interaction between the two components determines the overall level of yield of a given crop and the level of its loss due to competition for life factors between the crop and weeds. In modern systems of agro-technologies, the main task of designing agrophytocenoses is to achieve such a density of plants per unit area, which would ensure the optimality of their growth processes, the maximum realization of the potential of their genotype and guarantee the resulting success of competitiveness in relation to the main harmful weed species. A correctly formed cenosis thus provides not only high levels of desired productivity, but also provides a significant reduction of herbicide load in the technology of cultivation of the crop. On the other hand, between cultivated plants and weeds in the cenosis there are multifactorial systemic relationships, the nature of which is determined by the properties of the life strategy of the latter, according to which violents (C), patients (S), explerents (R) and transitional strategies (CS; CR; SR; CSR). Such complexity of biologic-competitive relationships despite the relative study of biology and reproductive tactics of a number of common weeds determines the search for optimal sowing parameters for each crop separately, providing high starting levels of competitiveness of cultivated plants in relation to the main weeds with a pronounced dominant life strategy in cenoses. This confirms the relevance of our research and its significance for agrotechnological practice.

In our previous publications, we noted that oilseed radish has positive features from the position of herbocompetition, which is due to high growth rates, positive reaction of the increase in total phytomass when changing the width of row spacing and intra-row spacing, intensive branching of the stem and a high degree of denudation, intensive indicators of photosynthetic potential growth starting from the stem stage.

However, there are a number of reservations regarding oilseed radish. In particular, the cessation of growth processes during the fruiting period (especially in the phase of yellow-green and yellow pods) leads to intensive weed growth, and in case of lodging of oil radish crops – to the dominance of weed vegetation in the upper tier of stem cenosis. The crop is also characterized by an intensive reduction in the number of leaves from the phase of yellow-green pod, which also contributes to intensive weed regrowth, especially in the final stages of vegetation of the crop. It should be taken into account in the strategy of controlling the number of weeds in agrocenoses of oilseed radish and its tendency to lodging at the final stages of vegetation, starting from the microstage of phenological development when 50% of pods have reached the final size (BBCH 75). The prolonged flowering period, which is combined with a long phase of pod formation and seed ripening on the background of a medium degree of lodging of the crop leads to increased dominance of weed plants in the microstage period of green-full pod ripeness (BBCH 75–89). Due to these features, the cenosis of oil radish is characterized by oscillatory character in the vertical dominance of certain biological groups of weeds. The total number of weed species identified in the surveys in different years of research is 38, which belong to 33 genera (Table 4.5).

Among the species, the most common families are Asteraceae, Brassicaceae and Poaceae – a total of 50.0 % in the total structure of the ratio. In general, the highest occurrence (dominance) including under conditions of frequent excess of EFV level in the crop was established for such spring weed species as field cabbage (*Brassica campestris* L.), wild radish (*Raphanus raphanistrum* L.), field mustard (*Sinapis arvensis* L.), white chaff (*Chen arvensis* L.). L.), white marestail (*Chenopodium album* L.), scabrous mountain (*Polygonum scabrum* Moench), tansy (*Amaranthus retroflexus* L.), common platypus (*Echinochloa crus-galli* L.), bristlecone blue (*Echinochloa crus-galli* L.), blue bristlecone (*Setaria glauca* L.), green bristlecone (*Setaria viridis* L.), stem-branching bramble (*Lamium amplexicaule* L.), small-flowered Galinsoga (*Galinsoga parviflora* Cav.). Wintering annuals include wild lettuce, compass lettuce (*Lactuca serriola* L.), clinging mayflower (*Galium aparine* L.), common thistle (*Rocket-cress* R. Br.), field broom (*Thlaspi arvense* L.), shepherd's purse (*Capsella bursa-pastoris* (L.) Medic.), chamomile (*Tripleurospermum inodorum* (L.) Sch. Bip.), *Stellaria media* (L.)).

The spectrum of perennial weeds is represented in the agrocenosis of oilseed radish by such weeds as creeping wheatgrass (*Elymus repens* (L.) Gould), field horsetail (*Equisetum arvense* L.), field thistle (*Sonchus arvensis* L.), field thistle (*Cirsium arvense* L.), field thistle (*Convolvulus arvensis* L.), field dandelion (*Taraxacum officinale* Wigg.), Tatar lettuce

(*Lactuca tataricia*), bitter wormwood (*Artemisia absinthium* L.), common wormwood (*Artemisia vulgaris* L.).

Until the phenological phase of the beginning of stemming (BBCH 36–52) the lower tier of cenosis is occupied by such weeds as creeping wheatgrass (*Elymus repens* (L.) Gould), horsetail (*Equisetum arvense* L.),medicinal dandelion (*Taraxacum officinale* Wigg.), scabrous mountain (*Polygonum scabrum* Moench), bluebunchgrass (*Setaria glauca* L.), bristlecone green (*Setaria viridis* L.), stem-branch (*Lamium amplexicaule* L.), small-flowered Galinsoga (*Galinsoga parviflora* Cav.), field broom (*Thlaspi arvense* L.), shepherd's purse (*Capsella bursa-pastoris* (L.) Medic.), chamomile unguent (*Tripleurospermum inodorum* (L.) Sch. Bip.), middle starflower (*Stellaria media* (L.)).

Taking into account certain regularities of species structure of weed infestation of oilseed radish agrocenosis, one of the stages of our research was to study the peculiarities of formation of the number of individual weed species that belong to different growth tiers in the context of different technological approaches to pre-sowing design of oilseed radish cenosis (Table 4.5). The results obtained show that the life strategy of individual weed species differs with the influence of factors put to study in the experiment. Thus, the condition of years were the most determinant in the formation of the number of bristlewort (Setaria glauca L.) – factor A 28.38 %, and the least – for the number of wheatgrass (Elymus repens (L.) Gould) (A – 19.42 %).

Stay in the same altitudinal tier with oilseed radish plants: field cabbage (*Brassica campestris* L.), wild radish (*Raphanus raphanistrum* L.), field mustard (*Sinapis arvensis* L.), white mungbean (*Chenopodium album* L.), tansy (*Amaranthus retroflexus* L.), common chickweed (*Echinochloa crus-galli* L.), wild lettuce, compassion (*Echinochloa crus-galli* L.). L.), tansy (*Amaranthus retroflexus* L.), common chickweed (*Echinochloa crus-galli* L.), wild, compass lettuce (*Lactuca serriola* L.), tussock (*Galium aparine* L.), common thistle (*Rocket-cress* R. Br.), field creeper (*Convolvulus arvensis* L.). The dominant role in the cenosis, beyond the altitudinal gradient, is occupied by such weeds as field thistle (*Sonchus arvensis* L.), field thistle (*Cirsium arvense* L.), Tatar lettuce (*Lactuca tataricia*), bitter wormwood (*Artemisia absinthium* L.), common wormwood (*Artemisia vulgaris* L.).

Table 4.5

Family-species spectrum of weeds in the agrocenosis of oilseed radish variety 'Zhuravka' in the system of averaged indicators of technological options of cenosis construction (average for 2013–2018 for the phase of green pod (BBCH 75–76)) (Tsytsiura, 2019)

Plant Genus	Number of species			Number of births		
	X_{av}, units.	R, units	%	X_{av}, units.	R, units	%
Asteraceae	7	4–10	18.42	5	3–7	15.15
Brassicaceae	7	5–8	18.42	6	5–8	18.18
Poaceae	5	3–7	13.16	5	3–6	15.15
Boraginaceae	4	1–5	10.53	4	3–5	12.12
Caryophyllaceae	3	2–5	7.89	2	1–4	6.06
Fabaceae	3	1–4	7.89	4	2–6	12.12
Chenopodiaceae	4	2–5	10.53	3	2–5	9.09
Euphorbiaceae	2	1–3	5.26	2	1–3	6.06
Lamiaceae	3	1–3	7.89	2	1–3	6.06

For the phenological interval of microstages from the green pod phase to the stage of full yellow ripeness of pods (BBCH 76–84), the character of visot dominance changes towards the weeds that previously occupied the middle and higher tier in relation to the height of oil radish plants (Fig. 4.4). The very factor of lodging of agrocenoses of oilseed radish, studied by us in a single complex of development of adaptive technological strategies of cultivation of the crop in the conditions of Praoberezhnaya Lesostepi of Ukraine (Tsitsyura, 2018), shows a high probability of lodging at a seeding rate of more than 2.0–2.5 million pieces/ha of germinating seeds on the background of full fertilization 60 and above kg/ha of active ingredient. This implies a higher probability of changes in the height dominance of weeds and a general increase in their number due to a decrease in plant competitiveness.

Taking into account certain regularities of species structure of weed infestation of oilseed radish agrocenosis, one of the stages of our research was to study the peculiarities of formation of the number of individual weed species that belong to different growth tiers in the context of different technological approaches to pre-sowing design of oilseed radish cenosis (Table 4.6).

Table 4.6

Numbers of individual weed species in the agrocenosis of oilseed radish variety Zhuravka depending on the technological parameters of its design (average for 2013–2018) (Tsytsiura, 2019)

Seeding rate (mln pcs ha^{-1} of germinated seeds) (factor B), sowing method (factor C)	Fertilizer rates (factor D)	Number of weeds for the period of full green pod phase (BBCH 75–79), pcs m^{-2}				
		Chenopodium album L	*Amaranthus retroflexus* L	*Setaria glauca* L.	*Elymus repens* L. Gould	*Cirsium arvense* L.
4,0 million, row	Without fertilizer	4.6 ± 0.8	1.1 ± 0.9	5.4 ± 2.0	1.6 ± 0.3	2.1 ± 0.2
	$N_{30}P_{30}K_{30}$	4.1 ± 0.9	1.5 ± 1.2	5.3 ± 2.2	1.4 ± 0.5	2.1 ± 0.3
	$N_{60}P_{60}K_{60}$	3.7 ± 1.2	1.4 ± 1.0	5.1 ± 2.5	1.2 ± 0.6	2.3 ± 0.3
	$N_{90}P_{90}K_{90}$	4.0 ± 1.5	1.8 ± 0.9	5.6 ± 2.7	1.2 ± 0.8	2.6 ± 0.4
3,0 million, row	Without fertilizer	4.5 ± 1.3	1.1 ± 0.8	5.1 ± 2.4	1.4 ± 0.4	1.9 ± 0.3
	$N_{30}P_{30}K_{30}$	4.0 ± 0.9	1.6 ± 1.0	5.5 ± 2.5	1.5 ± 0.5	2.0 ± 0.4
	$N_{60}P_{60}K_{60}$	3.4 ± 0.8	1.5 ± 1.0	5.2 ± 2.3	1.5 ± 0.5	2.2 ± 0.4
	$N_{90}P_{90}K_{90}$	3.7 ± 1.4.	2.1 ± 1.4	5.8 ± 2.7	1.7 ± 0.7	2.4 ± 0.5
2,0 million, row	Without fertilizer	4.4 ± 0.7	1.1 ± 1.0	5.6 ± 1.9	1.6 ± 0.4	2.2 ± 0.4
	$N_{30}P_{30}K_{30}$	4.5 ± 0.8	1.4 ± 1.1	5.9 ± 2.5	1.9 ± 0.4	2.2 ± 0.3
	$N_{60}P_{60}K_{60}$	5.0 ± 0.8	1.6 ± 1.2	6.7 ± 2.2	1.9 ± 0.5	2.5 ± 0.5
	$N_{90}P_{90}K_{90}$	5.3 ± 1.0	2.3 ± 1.5	6.2 ± 2.5	2.2 ± 0.5	2.7 ± 0.5
1,0 million, row	Without fertilizer	5.3 ± 0.5	1.9 ± 1.0	7.4 ± 2.0	1.8 ± 0.3	2.4 ± 0.4
	$N_{30}P_{30}K_{30}$	5.7 ± 0.7	2.1 ± 1.2	8.1 ± 2.2	1.8 ± 0.5	2.5 ± 0.6
	$N_{60}P_{60}K_{60}$	6.0 ± 0.6	2.7 ± 1.4	8.5 ± 2.5	2.1 ± 0.6	2.7 ± 0.6
	$N_{90}P_{90}K_{90}$	6.2 ± 0.9	3.1 ± 1.6	8.7 ± 2.7	2.4 ± 0.6	2.9 ± 0.6
2,0 million, wide-row	Without fertilizer	5.7 ± 1.2	1.6 ± 0.6	6.7 ± 1.9	1.7 ± 0.3	2.1 ± 0.4
	$N_{30}P_{30}K_{30}$	5.5 ± 1.1	2.1 ± 0.8	6.9 ± 1.9	1.6 ± 0.4	2.3 ± 0.7
	$N_{60}P_{60}K_{60}$	5.4 ± 1.3	2.4 ± 0.8	6.4 ± 1.8	1.9 ± 0.5	2.4 ± 0.5
	$N_{90}P_{90}K_{90}$	6.8 ± 1.2	2.6 ± 1.0	6.6 ± 2.2	1.9 ± 0.6	2.7 ± 0.7

(End of Table 4.6)

1,5 million, wide-row	Without fertilizer	5.8 ± 0.8		1.6 ± 0.7		8.5 ± 2.3		2.1 ± 0.4		2.3 ± 0.5	
	$N_{30}P_{30}K_{30}$	6.2 ± 0.7		2.2 ± 1.0		8.9 ± 2.0		2.3 ± 0.5		2.5 ± 0.5	
	$N_{60}P_{60}K_{60}$	6.5 ± 1.4		2.4 ± 0.8		9.2 ± 2.4		2.5 ± 0.5		2.7 ± 0.7	
	$N_{90}P_{90}K_{90}$	7.3 ± 1.9		2.9 ± 1.2		10.8 ± 2.4		2.5 ± 0.7		3.2 ± 0.7	
1,0 million, wide-row	Without fertilizer	6.1 ± 0.7		1.7 ± 0.7		11.8 ± 2.7		2.2 ± 0.3		2.3 ± 0.6	
	$N_{30}P_{30}K_{30}$	7.4 ± 1.5		2.7 ± 1.0		12.4 ± 2.9		2.4 ± 0.4		2.5 ± 0.7	
	$N_{60}P_{60}K_{60}$	8.6 ± 1.7		3.0 ± 0.9		13.8 ± 3.1		2.5 ± 0.5		2.8 ± 0.7	
	$N_{90}P_{90}K_{90}$	9.3 ± 1.9		3.4 ± 1.3		14.5 ± 3.3		2.6 ± 0.5		3.4 ± 0.8	
0,5 million, wide-row	Without fertilizer	7.8 ± 1.2		2.5 ± 1.4		12.3 ± 3.2		2.4 ± 0.3		2.5 ± 0.7	
	$N_{30}P_{30}K_{30}$	8.4 ±1.1		2.8 ± 1.5		12.9 ± 3.4		2.6 ± 0.3		2.7 ± 0.8	
	$N_{60}P_{60}K_{60}$	9.6 ± 1.6		3.2 ± 1.6		14.2 ± 3.6		2.6 ± 0.4		3.2 ± 1.0	
	$N_{90}P_{90}K_{90}$	10.4 ± 1.8		4.0 ± 1.8		15.8 ± 4.1		2.8 ± 0.6		3.5 ± 1.2	
Factor A – conditions of the year		**LSD_{05} ps.m^{-2}**	**Influence of factor (%)**	**LSD_{05} ps.m^{-2}**	**Influence of factor (%)**	**LSD_{05} ps.m^{-2}**	**Influence of factor (%)**	**LSD_{05} ps.m^{-2}**	**Influence of factor (%)**	**LSD_{05} ps.m^{-2}**	**Influence of factor (%)**
A		0,055	27.50	0.043	23.82	0.186	28.38	0.047	19.42	0.048	20.15
B		0,032	26.23	0.025	9.56	0.107	27.81	0.027	8.20	0.028	6.38
C		0,045	17.45	0.036	8.88	0.152	17.82	0.038	7.96	0.039	6.79
D		0,045	2.75	0.036	2.90	0.152	3.94	0.038	0.90	0.039	1.82
AB		0,077	6.55	0.061	13.08	0.263	1.72	0.066	15.87	0.067	15.45
AC		0,109	6.04	0.087	15.41	0.372	1.73	0.093	16.42	0.095	16.12
AD		0,109	0.37	0.087	0.95	0.372	0.39	0.093	3.99	0.095	6.01
BC		0,063	3.15	0.050	4.05	0.215	7.12	0.054	3.85	0.055	4.15
BD		0,063	1.82	0.050	0.40	0.215	1.83	0.054	0.37	0.055	0.49
CD		0,089	1.72	0.071	0.92	0.303	3.80	0.076	0.99	0.078	0.69
ABC		0,155	4.54	0.123	14.49	0.525	0.75	0.132	15.52	0.135	15.56
ABD		0,155	0.33	0.123	0.74	0.525	0.32	0.132	0.92	0.135	0.88
ACD		0,219	0.74	0.174	2.13	0.743	0.78	0.186	2.57	0.191	2.42
BCD		0,126	0.21	0.100	0.59	0.429	2.86	0.108	0.53	0.110	0.69
ABCD		0,310	0.61	0.246	2.08	1.051	0.74	0.263	2.48	0.269	2.40

The results obtained show that the life strategy of individual weed species differs with the influence of factors put to study in the experiment. Thus, the conditions of the year were the most determinant in the formation of the number of bristlewort (*Setaria glauca* L.) – factor A – 28.38 %, and the least – for the number of wheatgrass (*Elymus repens* (L.) Gould) (A – 19.42 %). The greatest influence in the complex of factors B, C and D was established for the abundance of bluebunch wheatgrass (*Setaria glauca* L.) (total sum of influence 49.57 %). The least complex influence of technological factors of the experiment was observed for the number of field thistle (*Cirsium arvense* L.) – total amount of 14.99 %.

Thus, the most pronounced influence of the herb-competing effect of the oil radish cenosis was established for annual weeds with a narrow interval of biological plasticity against the background of high values of the abiotic response, which include the following weed groups: ephemerals, ardent early annuals, winter and wintering weeds with a short vegetation period in crops of cultivated plants. Other features of the formation of the weed population in oil radish crops in the study area were also established: firstly, the maximum variability of the average annual value was noted for annual weeds; secondly, the effect of fertilizers had different effectiveness for different types of weeds – with a general increase in the number of weeds against higher fertilizer backgrounds, the responsiveness of different species was significantly different. Thus, in the strategy of coupled regulation of the number of weeds and the format of seeding rates and plant density for the agrocenosis of oilseed radish, it is necessary to take into account the edaphic properties of individual weed species (for example, azotophilicity, etc.). Thirdly, the seeding rate in interaction with the row spacing of oilseed radish (factor B and C) had the most pronounced effect on the number of all presented weeds of different biological groups with a feedback nature (Figures 4.5–4.6). For this factor, the established long-term value of influence is at the level of 39–67% (the main component and its interaction).According to the presented graphs, the minimum number of each weed is noted at different intervals of the density of standing of oilseed radish plants, and the nature of the regression surface has individual features characteristic only of this type of weed. Thus, in the variant of white goosefoot (*Chenopodium album* L.), the minimum number in the average annual measurement corresponds to the interval of 3.0–3.5 million pcs./ha

Figure 4.4 – Height dominance in oilseed radish agrocenosis of bristlewort (*Setaria glauca* L.), white mary (*Chenopodium album* L.) (top position, 2016) and field thistle (*Cirsium arvense* L.) (bottom position, 2018) by brown pod phase (BBCH 83–86) in the 1.5 million, wide-row variant on $N_{90}P_{90}K_{90}$ background (Tsytsiura, 2019)

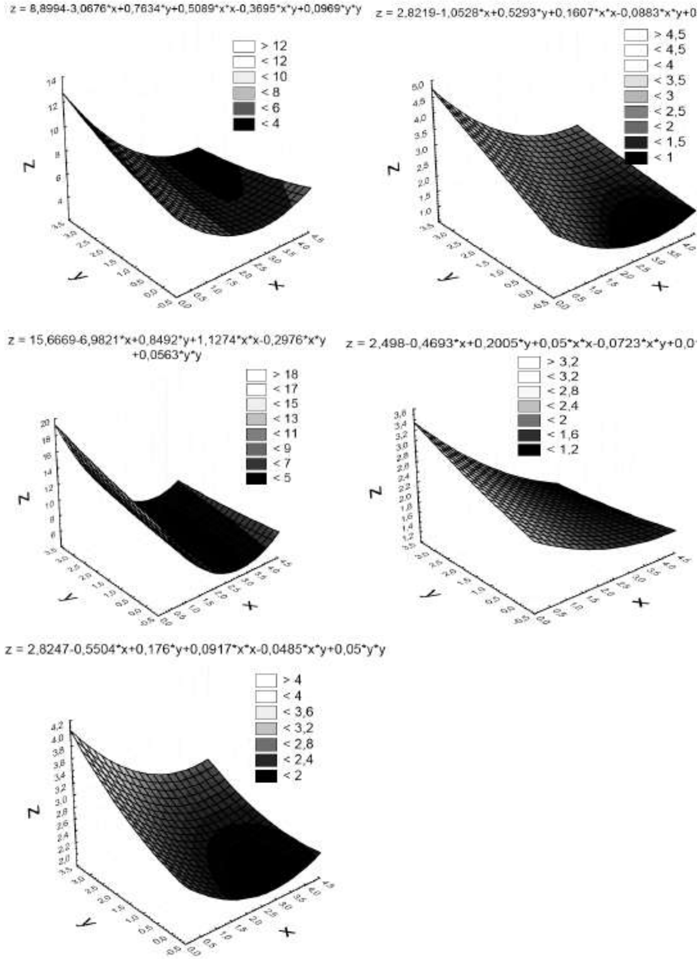


Figure 4.5 – Graphs of the dependence of the weed population (z-axis, pcs m^{-2}) on the seeding rate (x-axis, million pcs ha^{-1} of viable seeds) and fertilizer (y-axis, in index form: without fertilizers – 0, $N_{30}P_{30}K_{30}$ – 1; $N_{60}P_{60}K_{60}$ – 2; $N_{90}P_{90}K_{90}$ – 3.0). Consecutively from left to right and top to bottom: white goosefoot, retroflexed amaranth, glaucous foxtail, creeping wheatgrass, field thistle, average for 2013–2018 (Tsytsiura, 2019)

Figure 4.6 – Different types of weeds in oilseed radish agrocenosis, 2014–2024

of viable seeds with a fertilizer index of 1.5–2.0 (45–60 kg ha^{-1} of the active substance NPK). For the number of pigweed (*Amaranthus retroflexus* L.), the same minimum number is already at the parameters of seeding rates of 2.0–3.5 million pcs./ha of viable seeds and a fertilizer index of 0.0–1.5 (up to 45 kg ha^{-1} of the active substance NPK). For the number of foxtail grass (*Setaria glauca* L.) 2.5–3.5 million pcs/ha of viable seeds at a fertilizer index of 0.0–1.5 (up to 45 kg ha^{-1} of active substance NPK). Accordingly, for creeping wheatgrass (*Elymus repens* (L.) Gould) 3.5–4.5 million pcs/ha of viable seeds, 1.0–2.0 (30–60 kg ha^{-1}), and for field thistle (*Cirsium arvense* L.) – 2.0–3.5 million pcs ha^{-1} of viable seeds, 0.0–2.0 (0–60 kg ha^{-1}).

At the same time, we have established (Tsitsyura, Ya. et al. 2015) that the forage productivity of oilseed radish in the study area is the highest at a seeding rate of 2.0–2.5 million pcs ha^{-1} of viable seeds with the introduction of up to 60 kg ha^{-1} of NPK, and the maximum binary yield of leaf-stem mass and seeds is in the variant of 1.5–2.0 million pcs ha^{-1} of viable seeds with the introduction of the same up to 60 kg ha^{-1} of NPK. Thus, taking into account the level of the ratio of the number of weeds in the radically opposite experimental variants, oilseed radish should be classified as a plant with a high level of herb competition of a wide range of use.

To obtain the effective combined effect of reducing the overall weed infestation of crops while maintaining high levels of biological yield of the crop, it is advisable to use the following technological parameters of sowing: for the row option, 2.5–3.5 million pcs. ha^{-1} of viable seeds with the addition of $N_{30-60}P_{30-60}K_{30-60}$, for the wide-row option – 2.0–2.5 million pcs./ha of viable seeds with the addition of $N_{45-60}P_{45-60}K_{45-60}$.

4.2. Allelopathic potential of oilseed radish

Allelopathic approach in weed population control system isn't new, but it is based on biologic and physiologic regularities of agrocoenosis formation and development, which are based on the principles of vitality strategy of particular plant species and their competition both on the level of intraspecific and interspecific expression in the format of horizontal and vertical gradients (Bakhshayeshan–Agdam et al., 2015; Arroyo et al., 2018; VanVolkenburg et al., 2020). Application of the allelopathic factor is becoming more and more popular worldwide, given the intensive development of organic farming and crop production systems, and the formation of resistance in weeds to widely used active substances of herbicides. Development of this direction is also supported by aspects of climate change, which cause changes in the typology of the nature of the infestation of territories and the dominance of the most aggressive weed species, which are most adapted to the aridization of the territory's hydrothermal regime and are much more competitive than cultivated plant species (Rice, 1984; Brust et al., 2014; Duke, 2015; Jabran et al., 2015; Rueda–Ayala et al., 2015; Bhowmick et al., 2016; Hodgdon et al., 2016; Carvalho et al., 2019; Florence et al., 2019).

Allelopathic approaches are also important in considering agroecosystems towards development based on the maximal filling of ecological niches of certain species' existence and natural state of agrocenosis heterogeneity (Syed et al., 2014; Subtain et al., 2014; Singh et al., 2016; Kunz et al., 2016). Nowadays, highly specialized agroecosystems prevail, so their ability to support ecological balance through self–regulation mechanisms decreases. As a result, there is a growing environmental and genetic affliction of crops, as well as the need to use more chemical protection products on a larger scale. This inevitably enhances the process of destroying the mechanisms of natural landscape self–renewal (Blum, 2004; Reigosa et al., 2006; Macías et al., 2007).

From the standpoint of scientific study and application of allelopathic approaches to the determination of the competitiveness of cultivated plant species and dominant weeds in their cenosises have undergone a long and difficult formation period. Therefore, even though the issue is thoroughly studied, there are still many questions today without clear answers. It is well known that the carriers of allelopathic effect are physiologically active substances – collins, the chemical nature of which is extremely diverse and unstable even for one species (Grodzinsky, 1965; Rice, 1984; Inderjit and Keating, 1999; Awan et al., 2012; Iqbal & Fry, 2012; Gfeller et al., 2018). It means that even in terms of the chemistry of allelopathic activity itself, many factors determine it and can significantly limit it. The collins produced by plants themselves serve as ecological chemoregulators and are among the important environmental factors that determine the structure, dynamics and productivity of plant groupings. This biochemical phenomenon can seriously affect the germination of seeds and delay the development of further crops. At the same time, allelopathy can also have a positive effect on certain crops, which are able to inhibit the development of weeds by releasing biochemical compounds, while not harming cultivated plants. In this case, allelopathy is direct, i. e. from one crop to another (Grodzinsky, 1965; Rice, 1984; Lahdhiri et al., 2016; Sturm et al., 2016; Lemerle et al., 2017; Prinsloo and Plooy, 2018).

In modern practice, the allelopathic effect of plants is considered in terms of the following mechanisms: direct action of root exudations of a given species in the process of its growth and development (Grodzinsky, 1965; Rice, 1984; Izzet et al., 2004; Zimdahl, 2004; Yurchak, 2005; Jabran et al., 2015; Singh et al., 2016; Gfeller et al., 2018; Florence et al., 2019); the action of substances as a result of decomposition of plant residues of a given plant species in the system of technological application of sideration (Khanh et al., 2005; Hoffman and Regnier, 2006; Kruidhof et al., 2008; Hodgdon et al., 2016; Lahdhiri et al., 2016; Możdżeń et al., 2018); the artificially induced process of allelopathic impact due to the use of extracts from various parts of the plant in the process of their application for treatment of germinating seeds or their use in combination with traditional products of chemical and bioorganic origin, such as bioherbicides (Nagabhushana et al., 2001; Teasdale et al., 2003, 2007; Hoffman and Regnier, 2006; Pheng et al., 2010; Duke, 2015; Florence et al., 2019; Carvalho et al., 2019). As for the last option of the allelopathic effect, it should be noted that different parts contain different amounts of stopping substances (Grodzinsky, 1965; Rice, 1984; VanVolkenburg et al., 2020). According to Yurchak (2005), more collins are concentrated in leaves and generative organs; in the roots, their number is 1.6–9 times less, and the highest activity of plants is in the flowering phase.

Allelopathic activity of traditional cruciferous crops such as white mustard and rapeseed is known and determined by leaching and secretion of glucosinolates, and their hydrolysis to isothiocyanates inhibits germination and growth of weed seeds (Chew, 1988; Brown and Morra, 1996; Al–Khatib et al., 1997; Petersen et al., 2001; Turk and Tawaha, 2003; Norsworthy, 2003; Haramoto and Gallandt, 2004; Boydston and Al–Khatib, 2006; Lawley et al., 2012; Mohamed and El–gawad, 2014; Lemerle et al., 2017; Carvalho et al., 2019). Benzyl isothiocyanate, a product of white mustard decomposition, is phytotoxic for Abutilon theophrasti Medik. Allyl isothiocyanate, which was extracted from black mustard, inhibited germination of Bromus rigidus. Water extracts from rotten mustard residue

(Brassica kaber (D.C.)) were toxic for Echinochloa uusgalli var.Frumentacea (Roxb). Rapeseed leaves (Brassica napus L.), which had been put in the soil, suppressed the development of Chenopodium album, Amaranthus retroflexus and Echinochloa uusgal population, and their action was similar to the regular treatment with herbicides. White mustard and spring rapeseed leaves, which had been put into soil, reduced the abundance of Capsella bursa pastoris (L.) (Medic) and Kochia scoparia (L.) (Schrad). Winter rape, used as a green manure crop before planting potatoes, reduced weed density by 73–85% and biomass by 50–96% (Boydston, and Hang, 1995). In Russia, the rapeseed inclusion in crop rotation reduces the total number of weeds to 40%. Several other positive aspects regarding the impact of cruciferous crops on the number and germination of weeds were confirmed. On the other hand, there is a certain tendency for limited application of cruciferous crops in the system of allelopathic control of weeds to the already mentioned traditional white mustard, spring and winter rapeseed. As for oilseed radish, which has a full complex of beneficial features and belongs to the fodder–green–manure crops used in the system of organic (alternative) farming (Tsytsiura, & Tsytsiura, 2015), the question of allelopathy is poorly studied in comparison with other similar species: *Raphanus sativus* L. var. *longipinnatus*, *Raphanus sativus* var. *niger* J. Kern (Kunz et al., 2016) and even with wild radish species *Raphanus raphanistrum* (Norsworthy, 2003).

Given these factors, it is important to determine the allelopathic potential of oilseed radish as a fallow–grown and green manure component in the crop rotation for its effective application. This task has become the goal of our research. The research's working hypothesis is based on the assumption that the allelopathic potential of oilseed radish is sufficient for its effective use in farming systems with limited use of traditional herbicides, provided the appropriate realization of its allelopathic and competitive potential with respect to weeds.

Researches were carried out in laboratory conditions based on water extracts from weeds plants (water extraction method (in methodological variation Shahrokhi et al., 2011; VanVolkenburg et al., 2020)). The types of weeds used in the research are presented in Table 4.7.

Table 4.7

Weed species used in research and its symbol from EPPO codes database (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

Coded variant number (CVN)	Water extract from weeds (latin name)	EPPO Code	Coded variant number (CVN)	Water extract from weeds (latin name)	EPPO Code
1	2	3	4	5	6
0	Control (distilled water)	–	39	*Eryngium campestre* L.	ERXCA
1	*Capsella bursa–pastoris* L.	CAPBP	40	*Lepidium ruderale* L.	LEPRU
2	*Galium aparine* L.	GALAP	41	*Daucus carota* L.	DAUCA
3	*Ambrosia artemisiifolia* L.	AMBEL	42**	*Sinapis alba* L.	SINAL
4	*Stellaria media* (L.) Vill.	STEME	43	*Lepidium draba* L.	CADDR
5	*Setaria glauca* L.	SETPU	44	*Lactuca serriola* L.	LACSE
6	*Erigeron canadensis* L.	ERICA	45	*Lepidium campestre* (L.) Brown	LEPCA
7	*Carduus acanthoides* L.	CRUAC	46	*Polygonum aviculare* L.	POLAV
8	*Thlaspi arvense* L.	THLAR	47	*Portulaca oleracea* L.	POROL
9	*Cirsium arvense* (L.) Scopoli	CIRAR	48	*Fumaria officinalis* L.	FUMOF
10	*Cynodon dactylon* (L.) Pers.	CYNDA	49	*Descurainia Sophia* (L.) Prantl	DESSO
11	*Echinochloa crus–galli* (L.) P.Beauv.	ECHCG	50	*Cichorium intybus* L.	CICIN
12	*Polygonum lapathifolium* (L.) Delarbre	POLLA	51	*Avena fatua* L.	AVEFA
13	*Papaver rhoeas* L.	PAPRH	52	*Bromus secalinus* L.	BROSE
14	*Brassica campestris* (L.) Janchen	BRSRA	53	*Lamium purpureum* L.	LAMPU
15**	*Raphanus sativus* L. var. *oleiformis* Pers.	RAPSO	54	*Veronica hederifolia* L.	VERHE
16	*Agropyron repens* (L.) Gould	AGRRE	55	*Chondrilla juncea* L.	CHOJU
17	*Amaranthus retroflexus* L.	AMARE	56	*Crepis tectorum* L.	CVPTE

(End of Table 4.7)

1	2	3	4	5	6
18	*Taraxacum officinale* Weber	TAROF	57	*Lamium amplexicaule* L.	LAMAM
19	*Sonchus arvensis* L.	SONAR	58	*Cyclachaena xanthiifolia* Nuttall	IVAXA
20	*Raphanus raphanistrum* L.	RAPRA	59	*Digitaria ischaemum* (Schreber) Muhlenberg	DIGIS
21	*Tripleurospermum maritimum* (L.) Koch	MATMA	60	*Achillea millefolium* L.	ACHMI
22	*Galinsoga parviflora* Cavanilles	GASPA	61	*Senecio vernalis* (Waldstein & Kitaibel) Alexander	SENVE
23	*Chenopodium album* L.	CHEAL	62	*Spergula vulgaris* L.	SPRAR
24	*Convolvulus arvensis* L.	CONAR	63	*Poa annua* L.	POAAN
25**	*Brassica napus* L.	BRSNN	64	*Amaranthus blitoides* Watson	AMABL
26	*Rocket-cress* Brown	BARVU	65	*Plantago lanceolata* L.	PLALA
27	*Centaurea cyanus* L.	CENCY	66	*Acroptilon repens* (L.) de Candolle	CENRE
28	*Artemisia vulgaris* L.	ARTVU	67	*Erodium cicutarium* (L.) L'Héritier	EROCI
29	*Berteroa incana* (L.) de Candolle	BEFIN	68	*Panicum capillare* L.	PANCA
30	*Artemisia absinthium* L.	ARTAB	69	*Rumex acetosella* L.	RUMAA
31	*Rumex confertus* Willdenow	RUMCF	70	*Sisymbrium Loeselii* L.	SSYLO
32	*Setaria viridis* (L.) Palisot de Beauvois	SETVI	71	*Cuscuta campestris* Yuncker	CVCCA
33	*Polytrichum commune* L.	PTYCO	72	*Onopordon acanthium* L.	ONRAC
34	*Sinapis arvensis* L.	SINAR	73	*Echium vulgare* L.	EHIVU
35	*Arctium lappa* L.	ARFLA	74	*Polygonum convolvulus* (L.) Löve	POLCO
36	*Equisetum arvense* L.	EQUAR	75	*Bunias orientalis* L.	BUNOR
37	*Consolida regalis* Gray	CNSRE	76	*Aethusa cynapium* L.	AETCY
38	*Plantago major* L.	PLAMA	77	*Solanum nigrum* L..	SOLNI

** – species of cultivated plants, which were studied as scavengers (contamination) form in agrophytocoenosises.

Parts of the weed plants were selected during the flowering phase, with equal participation of parts of the root system, stem, leaves, and generative part in the general sample weight (the share of each element in the weight structure is 20%). The sample thus formed was milled and dried to an air–dry mass. The obtained samples were milled in a powder–like mass using a laboratory mill. Milled samples were stored in sealed bags for extracted air samples in a dark, dry place. The extract was produced in the following concentration variants (w v^{-1}): 16.0%, 8.0%, 4.0%, 2.0%, 1.0%, 0,5%, 0,25%. For extraction, an appropriate amount of milled weed sample was placed in a glass container, an appropriate amount of distilled water was added, which corresponded to the desired extraction concentration according to the sample weight mass/liquid volume ratio. The container was shaken so that the plant mass was completely immersed in distilled water, preheated to 40 ◦C. The container was covered with a lid. The extraction process lasted for 1 day at +22 ° C, while the water–soluble chemical compounds penetrated the solution. For better extraction, the samples were centrifuged. After 24 hours, the extracted solution was poured into a container and filtered out using filters.

To determine the allelopathic activity of weeds concerning oilseed radish, two experiments were conducted under the recommended methodological approaches (John et al. 2006; VanVolkenburg et al., 2020). The first one provided the study of oilseed radish germination when germinating 100 seeds with a single sowing fraction in a thermostatic mode with a temperature of 25 ° C on filter paper. Indicators of seed germination in all variants of germination were determined by the 6 day, the dynamics of germination was determined from the 3rd to 9th day with a 24–hour interval after laying samples on germination under the national standard of Ukraine (Seeds of agricultural crops. 2003). In germination capacity calculations, Kader (2005) and Association of Official Seed Analysts recommendations were considered (ISTA 1985; AOSA, 1990). The experiment was repeated four times. The obtained result was compared with the control point – germination on the background of distilled water. The seeds were considered as germinating upon the appearance of 2 mm radicle as described by Association of Official Seed Analysts (ISTA 1985; AOSA, 1990).

The second laboratory experiment (simulated, given the recommendations of Fujii et al. (2005)) envisaged seed germination with the use of plastic seedling cassettes with a useful volume of one cell of 50 cm^3, filled with well moistened soil substrate, accompanied by water extracts of the studied weed species according to the experiment scheme with the same volume and time interval (on the first, fifth and tenth days of germination). One processing variant included 10 cells of one variant with fivefold repeatability. Watering with distilled water to regulate the humidity of the substrate was carried out on the 3rd and 7th days of germination. Distilled water irrigation option is used as a control. The overall morphological development of plants was determined by dividing the selections in non–contiguous repetitions by the 18^{th} day of experiment (Figure 4.7).

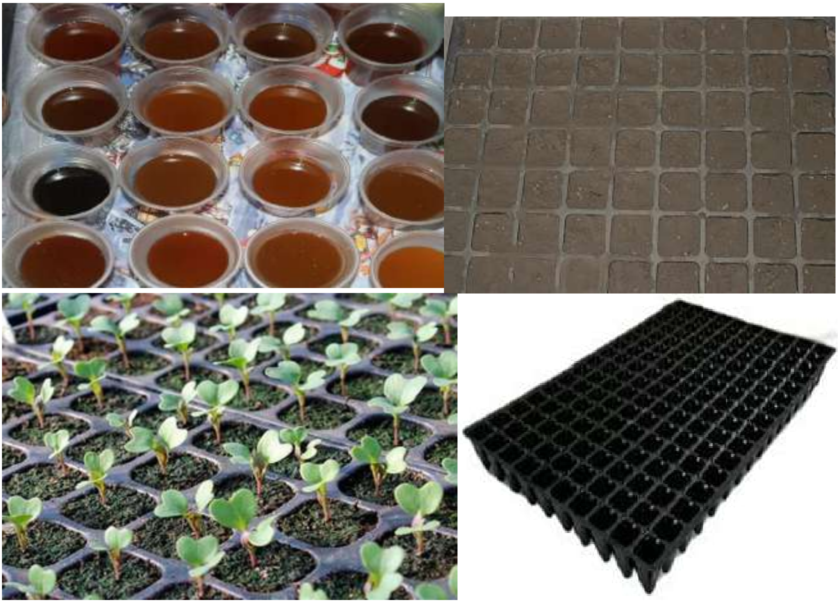


Figure 4.7 – Extracts from weeds plants before filtration and purification (left position) and system for soil germination of oilseed radish seeds during irrigation by weed extracts of different concentration (right position) (Tsytsiura, 2022)

The soil for the analysis was selected from the experimental field and was previously prepared for analysis according to the established methods, given the format of its use for laboratory bioindication (State standard of Ukraine, 2017). Soil substrate was selected from the Vinnytsia National Agrarian University experimental field (N 49°11′31″, E 28°22′16″) and matched the type of soil prevailing in the region, namely dark gray forest soils Luvic Greyic Phaeozem soils (IUSS Working Group WRB, 2015). Agrochemical field potential: humus content: 2,02–3,2%, lightly hydrolyzed nitrogen 67–92, mobile phosphorus 149–220, exchangeable potassium 92–126 mg kg^{-1} of soil at $pH_{кcl}$ 5,5–6,0.

Intertool MT–3006 electronic caliper was used for linear measurements. Weight characteristics of plants were determined using electronic laboratory scales Certus CBA–300–0,005. The content of dry matter in plants to calculate one of the indicators was determined by the method of thermostatic drying of the summary sample of plants obtained at soil–substrate germination on all repetitions of the variants of the experiment. Acidity of solutions in the experiment was determined using the electronic pH meter Smart Sensor AS218. Periodization of the oilseed radish phenological period was carried out in accordance with the BBCH scale, which is typical for cultures (Test Guidelines…, 2017).

The speed of germination (S) of each variant was calculated by the following equation as described by Einhellig et al. (1982) and Khandakar & Bradbeer (1983) in the interpretation of El–Khatib et al. (2004):

$$S = \frac{N_1}{1} + \frac{N_2}{2} + \frac{N_3}{3} \dots \frac{N_n}{n}$$

where N_1, N_2, N_3…N_n, ... is the proportion of seeds which germinated on day 1, 2, 3...n.

Coefficient of velocity (CV_i) was calculated by the adapted formula of Nasr & Mansour (2005):

$$CV_i = \left(\frac{\sum Ni}{T} \right),$$

where: N is the number of seeds germinated on day i and T is the number of days from sowing.

The rate of emergence (GR %) was determined by the formula of Marinov–Serafimov and Golubinova (2015):

$$GR_{\%} = 1 - \left[\frac{N_t - C_n}{N_c} \right] \times 100,$$

where N_t – germinated seeds in each treatment (%); N_c – germinated seeds in the control treatment (%); Cn – concentration, %.

Dynamic development index (DDI) was calculated by the formula of Marinov–Serafimov et al. (2017, 2019):

$$DDI = \left[\frac{t \log^{2}}{\log b - \log a} \right]$$

in which: a and b are the % of sprouted seeds, the root length, hypokotyl and seedlings (mm) and/or fresh biomass of the seedlings (g), accordingly in the control variant (a) and tested variants (b); t is the duration (days).

The growth and accumulation rates for fresh biomass of the root and seedlings were determined by the adapted formula of Dauta et al. (1990):

$$\mu = \left[\frac{\ln N_t - \ln N_0}{t} \right]$$

in which: N_t is the root length (mm), hypokotyl and seedlings or biomass for seedlings in the experimental variants; N_o is the root length (mm), hypokotyl and seedlings or biomass for seedlings in the control variant; t is the duration (days).

Tolerance Index (TI) was determined by the adapted formula of Tahseen and Jagannath (2015):

$$TI = \frac{LS_{ET}}{LS_{CT}} \times 100$$

where LS_{ET} – longest of seedlings in each experimental treatment, mm;

LS_{CT} – longest of seedlings in the control treatment, mm.

The index of plant development (GI) was assessed by the formula of Gariglio et al. (2002):

$$GI = \left[\frac{G}{G_0} \times \frac{L}{L_0} \right] \times 100 \text{ , \%}$$

where: G – germinated seeds (%) in each treatment; G_0 – germinated seeds (%) in the control treatment; L – average length (mm) of seedlings in treatment transformed into percentage in relation to the control treatment; L_0 – average length (mm) of the seedlings in the control treatment taken as 100%.

The germination root index (GRI) was assessed by the formula of Tiquia et al. (1996):

$$GRI = \left[\frac{G \times RG}{100}\right]$$

where: G – germinated seeds (%), RG – root growth (%).

Seedling vigor index (SVI) was determined using the equation poposed by Islam et al. (2009):

$$SVI = \left(\frac{S \times G}{100}\right)$$

where: S – seedling length in the treatments variant (mm); G – germinated seeds in the treatments variant (%).

Coefficient of allometry (CA) was calculated by the formula of Nasr & Mansour (2005):

$$CA = \frac{L_s}{L_r}$$

where: L_s is shoot length and L_r is root legth, mm.

Dry weight ratio (DWR) was calculated by the formula of Nasr & Mansour (2005):

$$DWR = \frac{DW_s}{DW_r}$$

where: DWs is dry weight of shoot (mg) and DWr is dry weight of root (mg).

Response index (RI) was determined by the equation by Williamson & Richardson (1988):

$$RI = \frac{T}{C} - 1 \text{ if } T<C; \quad RI = 1 - \frac{C}{T} \text{ if } T \geq C$$

where C – characteristic in the control treatment; T – characteristics in each treatment.

Percent inhibition (IR) was found according to the adapted formula of Surendra & Pota (1978):

$$IR = \frac{C - T}{C} \times 100 \text{ , \%}$$

where: C – parameter (length or biomass of shoot/root) in control; T – same parameter in experimental treatment.

Overall allelopathic potential (OAP) was determined by the equation of Tiquia et al. (1996) in interpretation equation of Smith (2013):

$$OAP = mean\ (IR_a + IR_b) / 100$$

where IR_a, a percent inhibition of the seedling growth at the lowest applied concentration of % w/v and IR_b percent inhibition of the seedling growth at the highest applied concentration.

The following classes were considered by the Smith (2013): OAP Score Description 0–0.25 Non–allelopathic (NA); 0.26–0.5 Moderately allelopathic (MA); 0.51–0.75 Highly allelopathic (HA); 0.76–1.0 Extremely allelopathic (EA).

The percentage of seed germination was calculated after preliminary arcsin–transformation following the formula, forwarded by Hinkelmann & Kempthorne (1994):

$$Y = \arcsin\left(\sqrt{\frac{x\%}{100}}\right).$$

Statistical evaluation Raw data from all analyses were processed using statistical software package Statistica 10.0. for Windows. ANOVA and Student/Fisher test (Hinnkelmann and Kempthorne, 1994) were used for testing the differences of allelopathic effect, between different aqueous extracts and also between oil radish seed and seedling reaction ($p<0.05$).

The research revealed that the obtained water extracts of the plant species under study had different color, smell and different optical properties (Fig. 1). Measured indicators of the solutions' acidity of the received water extracts showed a dynamic change to the decrease of this indicator from the maximum concentration of the water extracts in 16.0% to the minimum concentration of 0.25%, according to the regularities of the pH indicator at the gradual dilution of the solution with distilled water (Table 4.8).

It should be noted that solution acidity significantly differed in the range of two presented concentrations. In the concentration variant of 16.0%, given the typical pH grouping (Slessarev et al., 2016), its gradation value changed from very strongly acidic (pH 4.5–5.0) for species such as *Thlaspi arvense* L. (8 – here and hereinafter CVN), *Papaver rhoeas* L. (13), *Taraxacum officinale* Weber (18), *Sonchus arvensis* L. (19), *Raphanus raphanistrum* L. (20), *Tripleurospermum maritimum* (L.) Koch (21), *Chenopodium album* L. (23), *Brassica napus* L. (25), *Rocket-cress* Brown (26), *Artemisia absinthium* L. (30), *Sinapis arvensis* L. (34), *Arctium lappa* L. (35), *Equisetum arvense* L. (36), *Eryngium campestre* L. (39), *Lepidium* *ruderale* L. (40), *Sinapis alba* L. (42), *Lepidium draba* L. (43), *Portulaca oleracea* L. (47), *Fumaria officinalis* L. (48), *Senecio vernalis* (Waldstein & Kitaibel) Alexander (61), *Amaranthus blitoides* Watson (64), *Acroptilon repens* (L.) de Candolle (66), *Cuscuta campestris* Yuncker (71), *Polygonum convolvulus* (L.) Löve (74) to slightly acidic level (pH 6.1–6.5) for a species such as *Carduus acanthoid*es L. (7).

The chemical composition of water extracts was not studied, but the nature of changes in pH of their environment at high concentrations indicates the heterogeneity of the environment and its general inhibitory nature due to the existing pH index. This index is lower than the biological optimum for oilseed radish culture in soil and climatic zones of its cultivation at the level of 5.5–6.5 (Tsytsiura & Tsytsiura, 2015). Despite the deviation of the pH value of water extract for many species of analyzed plants from the biological optimum, it should be noted that for oilseed radish, its seeds germinated at the level of 1.7–2.4% at pH 4.7–4.9. For example, in the variant of seed germination in water extract from *Thlaspi arvense* L. and *Taraxacum officinale* Weber.

It should also be noted that the general dynamics of seed germination level growth along with dilution of the solution with distilled water at a corresponding decrease in its concentration doesn't show stable growth. We can draw some significant conclusions from the above: firstly, the change in pH value at the corresponding dilution of an extract from a certain plant species has different interval nature, which indicates a different level of the solution's effective buffering. It's confirmed by the general features of extractive solutions of different concentrations (Slessarev et al., 2016). Secondly, such nature of seed germination formation at different levels of its acidity indicates a corresponding level of the broad adaptive response of oilseed radish plants to changes in pH conditions of growth in the interaction with substances extracted from different parts of plants. This way, the pH of the extract has a corresponding effect on seeds' laboratory germination rate. In our opinion, it has a great impact on those species in which the optimal biological interval of pH is moved from slightly acidic to a neutral level (pH 6.1–7.3). The influence of pH index of water extracts is confirmed by the nature of correlation dependence between its value at the water extract concentration of 0.25% of different plant species and indicators of oilseed radish seed germination – 0.259 ($p < 0.05$), and the growth of bond density in the concentration variant of 4% – 0.358 ($p < 0.05$).

Table 4.8

Indicators of germination of oilseed radish seeds in water extracts of different weed species (under laboratory conditions), 2020 (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

CVN	pH at the concentr.		Concentration, w/v (%) (water extracts)							Concentration, w/v (%) (soil substrate)							OAP (1–4%)	OAP (1–4%)
	0.25	16.0	0.25	0.5	1.0	2.0	4.0	8.0	16.0	0.25	0.5	1.0	2.0	4.0	8.0	16.0	water substrate	soil substrate
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0	7.0	7.0	92.4	92.7	92.8	93.5	91.4	92.6	93.4	91.6	90.3	89.8	90.6	89.2	88.7	90.2	–	–
1	6.8	5.2	85.8	73.2	47.3	21.6	10.3	1.1	0.0	89.3	78.9	58.7	30.2	16.8	1.9	0.9	0.58	0.48
2	6.3	5.1	71.8	62.5	55.5	11.5	6.5	0.0	0.0	75.3	68.7	57.8	20.2	15.4	0.0	0.0	0.58	0.49
3	6.5	5.7	70.7	62.1	52.4	34.2	16.2	0.0	0.0	76.9	68.9	56.3	42.5	19.6	0.8	0.0	0.53	0.47
4	6.4	5.6	86.7	84.2	78.3	53.3	24.1	3.9	1.6	87.4	86.9	83.1	61.8	28.7	5.1	2.9	0.38	0.31
5	6.3	5.2	78.5	71.6	67.2	37.5	28.3	2.8	0.0	81.8	78.9	72.5	44.5	32.6	3.6	0.0	0.41	0.35
6	6.1	5.4	84.7	78.8	74.5	59.2	38.5	6.1	2.7	87.2	81.4	77.9	62.3	41.6	6.9	3.5	0.34	0.28
7	6.6	6.1	76.2	70.8	62.6	49.3	27.2	1.4	0.0	80.2	75.3	69.5	51.8	33.5	2.1	0.0	0.43	0.35
8	6.8	4.7	69.7	61.3	49.2	35.5	19.4	3.9	1.5	77.6	67.2	54.7	42.6	23.5	5.2	2.6	0.52	0.46
9	6.3	5.4	65.9	48.2	37.3	19.1	9.2	0.0	0.0	68.9	53.6	44.7	23.8	15.2	0.0	0.0	0.63	0.54
10	6.4	5.5	82.6	73.4	67.2	29.2	14.2	2.7	0.0	83.9	77.2	74.3	34.5	19.2	3.2	0.0	0.48	0.40
11	6.5	5.1	73.6	61.8	52.4	21.5	8.3	0.0	0.0	78.9	65.8	56.9	29.2	13.8	0.0	0.0	0.57	0.47
12	6.2	5.3	68.4	58.1	49.5	28.4	16.1	0.0	0.0	72.6	60.3	55.8	32.4	20.9	0.0	0.0	0.54	0.45
13	6.0	4.7	69.7	57.3	29.6	14.4	6.1	0.0	0.0	72.6	60.8	35.6	21.4	10.9	0.0	0.0	0.68	0.61
14	6.5	5.7	70.5	56.7	38.5	9.3	3.2	0.0	0.0	74.8	60.3	42.6	12.6	7.8	0.0	0.0	0.67	0.60
15	6.1	5.5	67.2	45.9	34.8	9.5	2.4	0.0	0.0	70.3	48.9	39.6	11.4	5.2	0.0	0.0	0.72	0.68
16	6.2	5.3	78.9	60.9	42.2	26.2	10.4	1.8	0.0	82.4	63.8	44.6	32.8	12.8	2.9	0.0	0.60	0.56
17	6.3	5.1	60.9	42.7	33.6	17.1	5.5	0.0	0.0	63.2	44.8	35.6	19.6	6.9	0.0	0.0	0.67	0.64
18	6.2	4.9	89.5	84.5	77.4	31.5	18.4	6.2	2.4	90.4	86.5	79.6	34.2	21.3	6.8	3.6	0.41	0.36
19	5.8	4.8	80.2	67.9	58.5	19.2	7.2	0.0	0.0	83.6	71.3	60.4	21.3	8.6	0.0	0.0	0.56	0.52
20	6.0	4.8	67.4	51.2	38.7	21.4	3.6	0.0	0.0	70.8	53.6	40.8	23.6	5.1	0.0	0.0	0.67	0.63
21	5.9	4.8	78.3	50.8	41.9	24.2	8.4	0.0	0.0	80.4	52.8	43.6	29.3	11.5	0.0	0.0	0.61	0.57
22	6.4	5.3	63.3	42.7	35.6	21.5	11.5	2.2	0.0	65.9	46.2	40.5	23.5	13.8	3.4	0.0	0.62	0.57

(End of Table 4.8)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
23	6.0	4.9	67.2	46.2	29.7	18.6	7.2	0.0	0.0	69.1	48.4	32.3	20.8	9.1	0.0	0.0	0.67	0.63
24	6.2	5.3	62.8	50.2	41.9	26.7	9.3	0.0	0.0	64.8	52.6	43.5	30.4	11.6	0.0	0.0	0.61	0.57
25	5.6	4.7	65.9	58.1	47.8	32.4	11.4	0.0	0.0	68.7	59.6	49.6	34.5	13.9	0.0	0.0	0.57	0.53
26	5.9	4.9	83.4	47.9	39.6	28.5	14.1	0.0	0.0	85.1	53.6	40.8	32.3	15.6	0.0	0.0	0.59	0.56
27	6.7	5.6	90.1	78.4	68.7	47.2	30.2	6.8	4.2	90.8	81.3	70.4	49.2	33.5	7.9	5.7	0.40	0.35
28	6.0	5.1	86.7	73.6	60.3	36.5	17.5	3.1	0.0	87.9	74.5	62.4	39.3	19.8	4.0	0.0	0.49	0.45
29	6.3	5.2	75.6	64.5	55.4	32.4	18.2	0.0	0.0	78.1	66.7	57.8	33.9	21.3	0.0	0.0	0.50	0.46
30	5.9	5.0	86.1	70.3	57.8	27.8	11.3	2.4	0.0	87.4	71.8	62.1	30.9	12.6	3.7	0.0	0.53	0.49
31	6.0	5.2	90.1	82.6	78.2	44.2	9.6	1.1	0.0	90.8	83.9	80.4	45.8	10.9	1.8	0.0	0.46	0.42
32	6.2	5.1	75.2	66.3	51.5	36.5	17.2	4.1	0.0	77.6	67.4	53.8	38.4	19.6	4.9	0.0	0.52	0.48
33	6.3	5.3	64.3	51.7	37.8	18.5	9.3	1.5	0.0	66.8	52.6	39.3	20.6	11.4	2.4	0.0	0.62	0.59
34	5.7	4.8	69.4	57.8	45.5	19.3	3.2	0.0	0.0	70.8	59.3	47.2	20.8	3.9	0.0	0.0	0.64	0.62
35	5.9	5.0	89.6	84.2	72.6	56.4	10.4	1.7	0.0	90.4	85.6	73.9	57.8	11.8	2.1	0.0	0.48	0.44
36	5.6	4.9	84.7	71.3	52.4	38.8	5.1	0.0	0.0	80.4	70.6	51.2	37.6	4.8	0.0	0.0	0.60	0.59
37	6.3	5.2	84.1	60.9	32.5	21.4	11.3	3.9	1.8	85.6	62.5	34.8	22.6	12.8	5.2	2.6	0.63	0.60
38	5.6	5.3	83.9	62.8	34.7	19.2	8.4	1.5	0.0	84.8	63.6	35.8	20.6	8.9	2.6	0.0	0.64	0.62
39	5.5	4.5	90.8	85.2	74.4	36.6	11.5	1.9	0.0	91.8	86.5	75.2	37.8	12.6	2.5	0.0	0.46	0.43
40	5.8	4.7	90.2	86.2	78.6	39.1	12.4	0.0	0.0	91	87.3	80.1	40.9	13.8	0.0	0.0	0.44	0.40
41	6.3	5.5	86.3	78.5	64.5	37.4	21.6	4.2	1.8	82.8	76.5	69.6	42.3	25.6	5.6	2.7	0.45	0.39
42	5.8	4.8	56.9	47.2	38.7	27.5	9.3	0.0	0.0	58.1	48.4	39.8	29.2	10.6	0.0	0.0	0.62	0.59
43	5.7	4.9	68.7	59.3	47.2	31.4	12.5	0.0	0.0	70.1	60.9	48.6	32.5	13.6	0.0	0.0	0.57	0.54
44	6.7	5.5	88.7	82.8	79.3	57.6	21.7	3.7	1.1	90.9	84.1	80.5	60.2	22.6	4.5	1.9	0.39	0.35
45	6.1	5.2	92.0	90.2	84.2	67.4	32.2	3.3	3.4	91.2	90.8	85.7	70.1	35.6	5.2	4.5	0.32	0.27
46	6.6	5.7	91.4	82.6	69.5	48.4	14.1	5.3	1.6	92.4	83.6	70.8	50.2	15.9	6.7	2.9	0.47	0.43
47	5.7	4.9	78.9	60.8	48.5	31.7	6.3	0.0	0.0	79.3	61.8	50.2	33.6	7.8	0.0	0.0	0.60	0.57
48	5.9	4.8	74.5	59.6	41.4	27.5	8.4	1.4	0.0	75.8	60.2	39.8	26.3	8.9	1.6	0.0	0.62	0.60
49	6.5	5.2	86.9	74.2	59.6	29.2	11.2	2.2	0.0	88.9	75.6	61.2	30.8	12.9	2.6	0.0	0.53	0.49
50	6.4	5.5	80.2	60.8	42.4	34.1	19.4	2.8	1.5	81.7	62.3	44.5	35.6	19.8	3.2	1.8	0.55	0.52
51	6.5	5.6	83.2	67.8	54.5	34.5	18.3	3.1	1.8	81.9	65.6	55.8	32.5	17.8	2.5	1.6	0.51	0.49
52	6.3	5.5	86.9	79.6	68.3	54.2	25.1	5.3	2.9	84.5	78.4	66.8	53.2	23.6	4.8	2.6	0.42	0.41
53	6.2	5.4	87.8	77.9	69.4	51.5	24.3	6.9	2.2	89.2	78.7	71.2	50.8	21.3	5.5	1.8	0.42	0.40

(End of Table 4.8)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
54	6.4	5.6	86.3	70.5	62.5	46.4	27.8	8.1	3.8	87.4	72.8	63.5	45.8	25.6	7.4	3.6	0.43	0.42
55	6.1	5.3	74.2	61.2	49.5	37.8	14.2	2.5	1.4	78.7	60.3	50.8	35.9	15.2	2.3	1.7	0.55	0.52
56	6.3	5.3	85.2	70.8	63.2	38.3	18.6	2.3	1.1	83.8	72.4	61.8	40.5	19.6	2.6	1.3	0.47	0.45
57	6.1	5.2	87.2	74.5	58.7	42.7	21.5	6.7	3.1	86.3	75.5	57.6	42.8	23.8	5.6	3.2	0.47	0.45
58	5.7	4.8	74.1	60.2	49.6	28.6	11.7	0.0	0.0	75.6	62.3	50.9	29.8	12.6	0.0	0.0	0.56	0.53
59	6.3	5.5	80.5	69.8	57.5	39.2	19.3	4.1	2.9	78.9	70.4	58.6	40.8	18.6	3.8	2.7	0.49	0.47
60	6.4	5.4	90.8	85.6	77.6	58.7	26.4	8.2	4.5	90.5	85.3	78.4	60.3	27.8	8.6	5.1	0.37	0.34
61	5.7	4.9	76.9	65.8	56.4	32.1	14.2	1.1	0.0	77.4	63.9	54.8	33.4	15.1	1.3	0.0	0.52	0.50
62	6.2	5.3	86.9	80.7	71.8	48.4	22.5	7.3	4.2	88.5	82.4	72.3	49.6	24.5	7.7	4.3	0.42	0.38
63	6.3	5.5	90.8	82.3	79.7	58.6	34.3	8.9	5.4	88.9	83.6	80.4	59.6	35.6	9.3	5.3	0.33	0.29
64	5.5	4.7	67.8	52.6	40.5	19.1	8.6	0.0	0.0	68.4	54.7	39.6	18.7	9.2	0.0	0.0	0.62	0.60
65	6.3	5.5	77.9	62.3	48.4	29.3	14.7	3.6	2.3	78.2	61.8	50.1	30.6	15.5	4.2	2.6	0.55	0.52
66	6.1	5.0	62.4	50.2	32.6	16.4	7.3	0.0	0.0	63.8	52.6	33.6	15.2	6.8	0.0	0.0	0.66	0.65
67	6.3	5.5	89.3	82.9	73.7	52.1	27.4	6.2	5.1	87.5	80.6	69.8	53.8	29.6	6.7	4.8	0.39	0.37
68	6.4	5.3	86.8	78.9	69.2	47.8	26.2	7.1	3.9	85.3	77.4	70.8	51.3	27.8	8.3	4.2	0.41	0.37
69	6.3	5.5	82.9	75.3	62.5	46.2	14.7	2.5	1.4	83.4	77.5	63.9	42.8	13.8	2	1.2	0.49	0.47
70	6.0	5.1	74.1	56.9	47.7	32.5	11.1	2.1	0.9	75.2	57.1	49.2	33.6	12.5	2.5	1.2	0.57	0.54
71	5.6	4.8	60.9	42.5	29.3	16.7	6.5	0.0	0.0	56.4	40.3	28.4	15.2	5.8	0.0	0.0	0.68	0.68
72	5.2	5.5	69.7	59.6	44.5	29.5	12.5	0.0	0.0	70.8	60.3	45.2	28.4	11.8	0.7	0	0.58	0.56
73	6.5	5.7	82.6	70.9	57.8	36.4	19.3	2.7	1.2	83.8	72.5	59.6	35.6	18.4	2.3	1	0.49	0.47
74	6.3	5.0	63.2	50.8	41.4	21.7	10.4	0.0	0.0	64.5	52.6	43.2	20.3	9.8	0.0	0.0	0.60	0.58
75	6.2	5.4	82.6	75.9	61.3	41.4	16.5	2.4	0.0	83.6	77.8	62.6	39.8	15.2	2.1	0.0	0.49	0.47
76	5.8	5.1	66.3	54.7	41.6	29.5	18.3	1.7	0.0	72.8	62.3	48.9	27.2	15.4	1.3	0.0	0.56	0.53
77	6.2	5.5	81.4	68.9	50.7	31.7	12.4	3.9	1.1	83.2	67.1	49.8	32.8	12.9	3.3	1.5	0.55	0.54
Average	*6,2*	*5,2*	*78,4*	*66,4*	*54,8*	*34,4*	*16,0*	*3,5*	*2,1*	*79,8*	*68,2*	*56,8*	*36,4*	*17,7*	*3,7*	*2,3*	*0,53*	*0,49*
$SSD_{0.05}$	0.1	0.3	1.8	1.6	1.4	1.2	1.0	–	–	1.9	1.8	1.7	1.5	1.4	–	–	0.036	0.047
Tukey's test: total number of comparable comparison pairs 3003, number of comparison pairs that were not included in 95% confidence interval (p_{adj}=0.492–1.000) 543 (18.08% of values that do not differ significantly in the 95% confidence interval)																		

SSD – The smallest significant difference between the values according to LSD test для $p< 0.05$; CVN – coded variant number.

It was also found that oilseed radish is very sensitive in terms of allelopathic effect. It is confirmed by laboratory germination results both in water and soil substrate already from the extract concentration level of 0.25%. At the same time, the extremely high concentration of the extract for most species is limited to 4.0%, with an interval of a significant decrease in laboratory germination of 1.0–4.0% (Fig. 2).

According to Grodzinsky (1965), this nature of reaction indicates both high allelopathic sensitivity of the species and its adaptive vitality tactics in the formation of its own cenosis in the overall cenosis of interactions between species diversity of competing plant species. In many studies (Inderjit, Keating K.I. 1999; Khanh et al., 2005; Izzet et al., 2006; Jabran et al., 2006; Kunz et al., 2016; Lahdhiri and Mekki, 2016), an allelopathic reaction in the range from 0.1% to 32.0 was observed for many plant species. At the same time, the reaction to an intensive decrease in seed germination is already determined from 0.5–1.5%. In some early studies (Grodzinsky, 1965), it is noted that the degree of the allelopathic reaction manifestation is conditioned both by the species introduction in terms of the time of its cultivation, and by the proximity to typical representatives of weed vegetation. In long–term agricultural use, the species spectrum of allelopathic reaction narrows to the most aggressive species, and vice versa, with limited territorial cultivation, the allelopathic sensitivity is higher. This is confirmed in our studies, given the fact that the intensity of oilseed radish cultivation in many regions is limited.

The nature of formation of the oilseed radish germination also differed at germination on filter paper (trivial water substrate of germination) and, respectively, in the variant of approximate imitation to field conditions – on the soil substrate. The presented averaged data show a general decrease in allelopathic effect on oilseed radish germination exactly when grown on the soil substrate by 0.2–2.0% depending on the extract concentration. The maximum difference is noted when comparing two germination variants in the concentration range of 0.25–2%, and the minimum one in the range of 8–16%. Moreover, the value of such reduction is species–specific. So, for the species *Capsella bursa–pastoris* L. (1) it ranged from 0.9 to 10.4%, for the species *Agropyron repens* (L.) Gould (16) 1.1–3.5%, and for the species *Polygonum aviculare* L. (46) 1.0–1.8%. This nature of allelopathic effect has also been noted in the researches of several scientists (Blum, 2004; Fujii et al., 2005; Subtain et al., 2014).

In these researches it is explained by the absorption and adsorption of a number of substances extracted into the solution during the extraction process. In fact, this confirms the statement that the allelopathic potential of a particular weed species is determined both by its stage phenological development and by the edaphic conditions of its growth and development, which determine both the vegetation intensity of the species, its vitality index, and the degree of influence of its root excretions, given the favorable soil fertility conditions for the species itself.

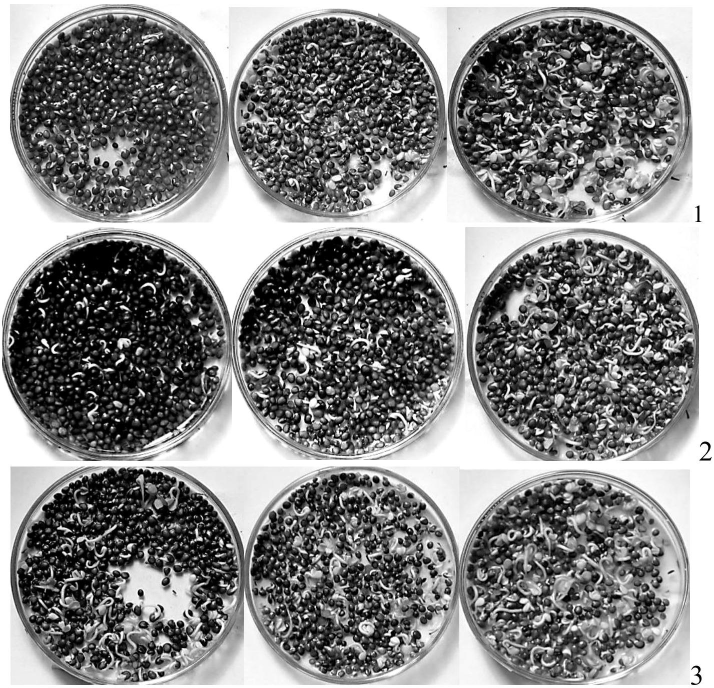


Figure 4.8 – As an example, from the overall totality of studied types of oilseed radish germination in water extracts of weeds of various concentrations (sequentially from left to right: 4.0, 2.0 and 1.0%) (1 – *Ambrosia artemisiifolia* L.; 2 – *Galium aparine* L.; 3 – *Carduus acanthoides* L.). (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

In our opinion, the difference in the allelopathic impact on seed germination for the two variants is a measure of the importance of soil conditions for the manifestation of herbal competition of this species in relation to the oilseed radish. We consider the fact that in its cycle of development, critical period for weed control (CPWC) is typical for the period from 5–7 to 12–15 days of vegetation (Tsytsiura, 2020), which determines a specific competition of this species in relation to other plant species (Lawley et al., 2012). An actual evidence of the dynamic nature of the formation of oilseed radish seed germination at changing concentration levels and its dependence on the nature of germination are the results of calculating such an indicator as the rate of emergence (GR %) (Table 4.9).

According to this indicator, the nature of changes in the oilseed radish laboratory germination has significant differences in comparison of soil and water germination substrate with an increase in favor of the soil substrate. The maximum oilseed radish sensitivity at germination stage with minimum extract concentration (0.25%) is noted for such weeds as Amaranthus retroflexus L. (17), Convolvulus arvensis L. (24), Acroptilon repens (L.) de Candolle (66), Polygonum convolvulus (L.) Löve (74) with the GR level in the range of 65.6–71.7%. The minimum indicator in the 96.6–99.9 range was observed in such weeds as *Taraxacum officinale* Weber (18), *Centaurea cyanus* L. (27), *Rumex confertus* Willdenow (31), *Arctium lappa* L. (35), *Eryngium campestre* L. (39), *Lepidium ruderale* L. (40), *Lepidium campestre* (L.) Brown (45), *Achillea millefolium* L. (60), *Poa annua* L. (63). That is, the minimum sensitivity at seed germination in oilseed radish is observed for weeds, the occurrence frequency of which in its cenosis is minimal. The very nature of the germination dynamics had a heterogeneous nature and species specificity from a slow–down nature to a nature with leap–scopic decline, which points in favor of the biochemical causes (Reigosa et al., 2006; Florence et al., 2019).

For a more detailed assessment of the nature of this dynamics, two indicators of speed of germination (S) and coefficient of velocity (CV_i) were used for the soil–free germination variant, which, as we found, is more biologically aggressive and needs to be evaluated typologically for the nature of similarity formation on an allelopathic background. These indicators are rarely applied to such research systems, but are very informative (Nasr & Mansour (2005)), as they demonstrate both the overall

Table 4.9

The rate of emergence (GR, %) of oilseed radish seeds in water extracts of different weed species (under laboratory conditions), 2020 (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

CVN	Concentration, w/v (%) (water extracts)					Concentration, w/v (%) (soil substrate)					CVN	Concentration, w/v (%) (water extracts)					Concentration, w/v (%) (soil substrate)				
	0.25	**0.5**	**1.0**	**2.0**	**4.0**	**0.25**	**0.5**	**1.0**	**2.0**	**4.0**		**0.25**	**0.5**	**1.0**	**2.0**	**4.0**	**0.25**	**0.5**	**1.0**	**2.0**	**4.0**
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
0	100	100	100	100	100	100	100	100	100	100	39	98.0	91.4	79.1	37.0	8.2	99.9	95.2	82.6	39.5	9.6
1	92.6	78.4	49.9	21.0	6.9	97.2	86.8	64.3	31.1	14.3	40	97.3	92.4	83.6	39.7	9.2	99.1	96.1	88.1	42.9	11.0
2	77.4	66.9	58.7	10.2	2.7	81.9	75.5	63.3	20.1	12.8	41	93.1	84.1	68.4	37.9	19.3	90.1	84.2	76.4	44.5	24.2
3	76.2	66.5	55.4	34.4	13.3	83.7	75.7	61.6	44.7	17.5	42	61.3	50.4	40.6	27.3	5.8	63.2	53.0	43.2	30.0	7.4
4	93.6	90.3	83.3	54.9	22.0	95.1	95.7	91.4	66.0	27.7	43	74.1	63.4	49.8	31.4	9.3	76.3	66.9	53.0	33.7	10.8
5	84.7	76.7	71.3	38.0	26.6	89.0	86.8	79.6	46.9	32.1	44	95.7	88.8	84.4	59.5	19.4	99.0	92.6	88.5	64.2	20.9
6	91.4	84.5	79.2	61.2	37.7	94.9	89.6	85.6	66.6	42.2	45	99.3	96.8	89.7	69.9	30.9	99.3	100	94.3	75.2	35.4
7	82.2	75.8	66.4	50.6	25.4	87.3	82.8	76.3	55.0	33.1	46	98.6	88.6	73.8	49.6	11.1	100.6	92.0	77.7	53.2	13.3
8	75.2	65.6	51.9	35.8	16.8	84.4	73.9	59.8	44.8	21.9	47	85.1	65.0	51.2	31.8	2.5	86.3	67.9	54.8	34.9	4.3
9	71.0	51.5	39.1	18.3	5.7	74.9	58.8	48.7	24.1	12.6	48	80.4	63.8	43.5	27.3	4.8	82.5	66.1	43.2	26.8	5.5
10	89.1	78.6	71.3	29.1	11.2	91.3	84.9	81.6	35.9	17.0	49	93.8	79.5	63.1	29.1	7.9	96.8	83.2	67.0	31.8	10.0
11	79.4	66.1	55.4	20.9	4.7	85.9	72.3	62.2	30.0	11.0	50	86.5	65.0	44.6	34.3	16.8	88.9	68.4	48.4	37.1	17.7
12	73.8	62.1	52.3	28.2	13.2	79.0	66.2	61.0	33.6	18.9	51	89.8	72.6	57.7	34.8	15.6	89.1	72.1	61.0	33.7	15.5
13	75.2	61.3	30.8	13.3	2.3	79.0	66.8	38.5	21.4	7.7	52	93.8	85.3	72.5	55.8	23.1	92.0	86.3	73.3	56.5	22.0
14	76.0	60.6	40.4	7.8	–0.9	81.4	66.2	46.3	11.7	4.3	53	94.8	83.5	73.7	52.9	22.2	97.1	86.6	78.2	53.9	19.4
15	72.5	49.0	36.4	8.0	–1.8	76.5	53.6	43.0	10.4	1.3	54	93.1	75.5	66.3	47.5	26.0	95.1	80.1	69.6	48.3	24.2
16	85.1	65.2	44.4	25.9	7.0	89.7	70.1	48.6	34.0	9.9	55	80.0	65.5	52.3	38.3	11.2	85.6	66.2	55.5	37.4	12.6
17	65.6	45.5	35.1	16.1	1.6	68.7	49.1	38.5	19.4	3.3	56	91.9	75.8	67.0	38.8	16.0	91.2	79.6	67.7	42.5	17.5
18	96.6	90.6	82.3	31.6	15.8	98.4	95.2	87.5	35.5	19.4	57	94.1	79.8	62.2	43.5	19.1	93.9	83.1	63.0	45.0	22.2
19	86.5	72.7	62.0	18.4	3.5	91.0	78.4	66.1	21.3	5.2	58	79.9	64.4	52.4	28.4	8.4	82.3	68.4	55.6	30.7	9.6
20	72.7	54.7	40.6	20.7	–0.4	77.0	58.8	44.3	23.8	1.2	59	86.9	74.8	60.9	39.8	16.7	85.9	77.4	64.1	42.8	16.4
21	84.5	54.3	44.1	23.7	4.8	87.5	57.9	47.4	30.1	8.4	60	98.0	91.8	82.5	60.6	24.5	98.5	93.9	86.2	64.3	26.7
22	68.2	45.5	37.3	20.9	8.2	71.7	50.6	44.0	23.7	11.0	61	83.0	70.4	59.7	32.2	11.2	84.2	70.2	59.9	34.7	12.4

(End of Table 4.9)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
23	72.5	49.3	30.9	17.8	3.5	75.2	53.0	34.9	20.8	5.7	62	93.8	86.5	76.3	49.6	20.2	96.3	90.7	79.4	52.5	23.0
24	67.7	53.6	44.1	26.4	5.8	70.5	57.7	47.3	31.3	8.5	63	98.0	88.2	84.8	60.5	33.2	96.8	92.0	88.4	63.6	35.4
25	71.0	62.1	50.4	32.5	8.1	74.7	65.4	54.1	35.9	11.1	64	73.1	56.2	42.6	18.3	5.0	74.4	60.0	43.0	18.4	5.8
26	90.0	51.1	41.6	28.3	11.1	92.6	58.8	44.3	33.4	13.0	65	84.0	66.7	51.1	29.2	11.7	85.1	67.9	54.7	31.6	12.9
27	97.2	84.0	73.0	48.3	28.7	98.9	89.5	77.3	52.1	33.1	66	67.3	53.6	34.1	15.4	3.6	69.4	57.7	36.3	14.6	3.1
28	93.6	78.9	63.9	36.9	14.8	95.7	81.9	68.4	41.2	17.7	67	96.4	88.9	78.3	53.6	25.6	95.3	88.7	76.6	57.2	28.7
29	81.5	69.0	58.6	32.5	15.5	85.0	73.3	63.3	35.2	19.4	68	93.7	84.6	73.5	49.0	24.3	92.8	85.2	77.7	54.4	26.7
30	92.9	75.3	61.2	27.6	8.0	95.1	79.0	68.0	31.9	9.6	69	89.4	80.7	66.3	47.3	11.7	90.8	85.3	70.0	45.0	11.0
31	97.2	88.6	83.2	45.1	6.1	98.9	92.4	88.4	48.3	7.7	70	79.9	60.8	50.3	32.6	7.8	81.8	62.7	53.7	34.9	9.5
32	81.1	71.0	54.4	36.9	14.4	84.4	74.1	58.8	40.2	17.5	71	65.6	45.3	30.5	15.7	2.7	61.3	44.1	30.5	14.6	2.0
33	69.3	55.2	39.7	17.6	5.8	72.7	57.7	42.7	20.5	8.3	72	75.2	63.8	46.9	29.4	9.3	77.0	66.2	49.2	29.1	8.7
34	74.8	61.8	48.0	18.5	–0.9	77.0	65.1	51.4	20.8	–0.1	73	89.1	75.9	61.2	36.8	16.7	91.2	79.7	65.3	37.1	16.1
35	96.7	90.3	77.2	58.2	7.0	98.4	94.2	81.2	61.6	8.7	74	68.1	54.3	43.5	21.1	7.0	70.1	57.7	47.0	20.2	6.5
36	91.4	76.4	55.4	39.4	1.2	87.5	77.6	55.9	39.3	0.9	75	89.1	81.3	65.0	42.1	13.7	91.0	85.6	68.6	41.7	12.6
37	90.7	65.2	33.9	20.7	8.0	93.2	68.7	37.6	22.7	9.9	76	71.5	58.5	43.8	29.4	15.6	79.2	68.4	53.3	27.8	12.8
38	90.5	67.2	36.3	18.4	4.8	92.3	69.9	38.8	20.5	5.5	77	87.8	73.8	53.6	31.8	9.2	90.6	73.8	54.3	34.0	10.0

germination intensity and its dynamic nature for each additional day of the germination period. With respect to the first indicator (Fig. 4.9), significant differences were found with a concentration fluctuation of 4.0% from 9.10 for *Ambrosia artemisiifolia* L. (3) by 16.88 for *Achillea millefolium* L. (60). For water extract concentration of 1.0% – from the minimum value of 14.10 for *Raphanus sativus* L. var. *oleiformis* Pers. (15) (i.e. for the culture itself) up to the maximum value of 17.21 for *Papaver rhoeas* L. (13) at level 16.48 on control.

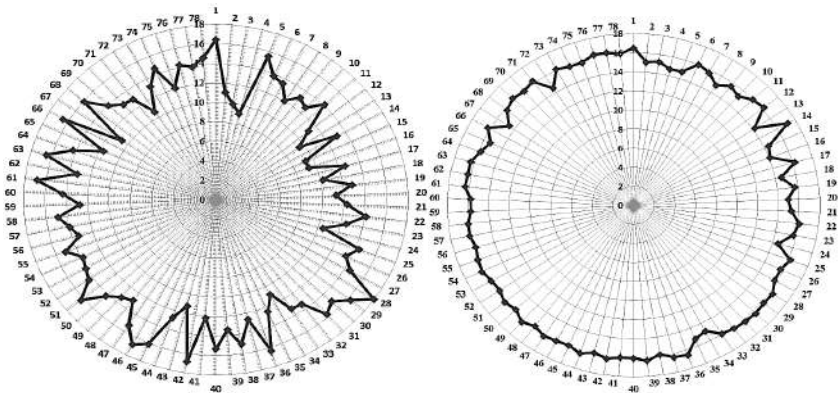


Figure 4.9 – The speed of germination (S) of each variant at concentrations of water extract 4% (left position) and 1% (right position), 2020. (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

The obtained values of speed of germination (S) allowed to identify several types of oil radish seed germination rate under the impact of water extracts from various weeds. According to our estimates, the indicator can be functionally divided into three groups: 13–17 units – the majority of germinated seeds appear on 3–5 days of germination (typical group representatives: *Stellaria media* (L.) Vill. (4), *Cynodon dactylon* (L.) Pers. (10), *Convolvulus arvensis* L. (24), *Rocket-cress* Brown (26), *Artemisia vulgaris* L. (28), *Artemisia absinthium* L. (30), *Arctium lappa* L. (35), *Daucus carota* L. (41), *Lepidium campestre* (L.) Brown (45), *Achillea* *millefolium* L. (60); 11–13 units – the majority of germinated seeds appear on 5–7 days (typical group representatives: *Capsella bursa–pastoris* L. (1), *Raphanus raphanistrum* L. (20), *Equisetum arvense* L. (36), *Sinapis alba* L. (42), *Portulaca oleracea* L. (47), *Amaranthus blitoides* Watson (64), *Cuscuta campestris* Yuncker (71), *Polygonum convolvulus* (L.) Löve (74)); 8–11 units – an extended nature of similarity dynamics is formed with a shift from 5 to 9 days (typical group representatives: *Galium aparine* L. (2), *Ambrosia artemisiifolia* L. (3), *Echinochloa crus–galli* (L.) P.Beauv. (10), *Polygonum lapathifolium* (L.) Delarbre (12), *Brassica campestris* (L.) Janchen (14), *Amaranthus retroflexus* L. (17), *Chenopodium album* L. (23)). According to our observations, the latter variant is also characterized by the effect of the so–called sleeping seed, i.e. swollen forms with evident signs of germination initiation. For example, it is clearly demonstrated by the extreme left position 1 of Figure 4.8 in case of applying an extract from *Ambrosia artemisiifolia* L. (3). We have found that the weeds, which are dominant in oilseed radish agrophytocoenosises in the research area, belong to both the third and the second classification group of the indicator of speed of germination (S).

The typology of the conducted grouping is confirmed by the evaluation of the coefficient of velocity (CV_i) for two contrast concentrations of 4.0 and 1.0% at soil–free germination. This coefficient also allows estimating the interval rates of germinated seed formation (Nasr & Mansour, 2005). Statistical interpretation of the total array of variants by CV_i indicator in the interval of 3–9 days of germination for two concentrations of water extracts of 4.0 and 1.0% (Fig. 4.10) showed significant differences in each interval period under study. At the same time, the maximum range of values for both concentration variants is determined on the 3rd and 4th day of germination. The decrease in the concentration of the applied extract reduces the allelopathic pressure and normalizes the variable dynamic curve of germinated seed formation to the biologically optimal maximum similarity on the 3–5th day in the absence of allelopathic extracts, which agrees with a number of studies (Rice, 1984; Inderjit and Keating, 1999; Izzet et al., 2004; John et al. 2006; Golubinova & Ilieva, 2015; Duke, 2015), and the example for different types of weeds is clearly shown in Figure 4.11.

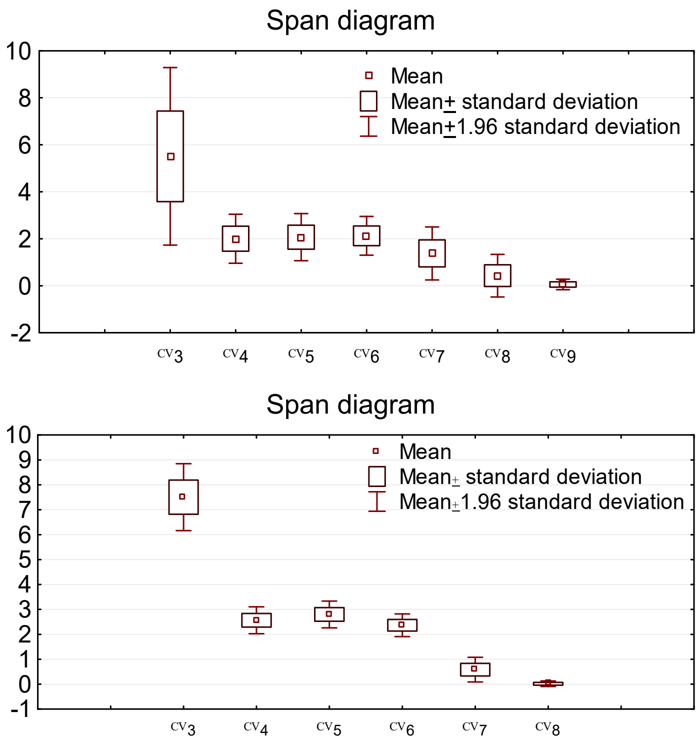
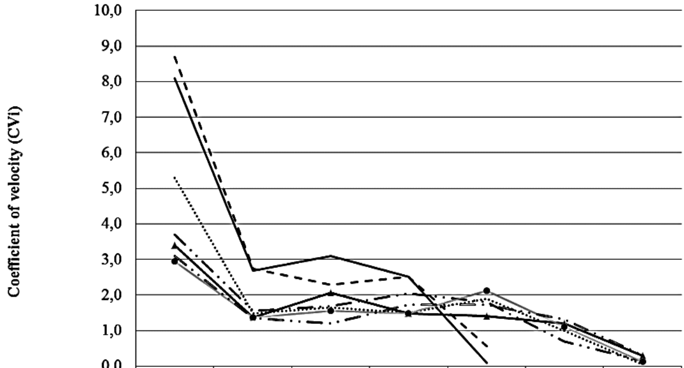


Figure 4.10 – The range of values for the coefficient of velocity (CV_i) for the studied group of weeds in the context of the third (CV_3) and the ninth day (CV_9) of germination using water extraction of weeds (concentration of 4.0% upper position, concentration of 1.0% lower position) (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

Obviously, given the large array of processed data, it is difficult to analyze each species in the system of similarity changes with different concentrations of the extract, but according to the results of recent studies (Smith, 2013; Jain et al., 2017; Możdżeń et al., 2018), such analysis can be successfully substituted by the evaluation of the species by the Overall allelopathic potential indicator (OAP) (Table 4.10).



	CV3	CV4	CV5	CV6	CV7	CV8	CV9
Control	8,1	2,7	3,1	2,5	0,1		
Echinochloa crus-galli (L.) P.Beauv.	3,4	1,4	2,1	1,5	1,4	1,2	0,3
Taraxacum officinale Weber	5,3	1,5	1,7	1,5	1,9	1,0	0,1
Lepidium campestre (L.) Brown	8,7	2,7	2,3	2,5	0,6		
Amaranthus blitoides Watson	3,7	1,6	1,7	2,0	1,8	0,7	0,1
Acroptilon repens (L.) de Candolle	3,0	1,4	1,6	1,5	2,1	1,1	0,1
Cuscuta campestris Yuncker	3,1	1,4	1,2	1,7	1,7	1,3	0,3

Figure 4.11 – Coefficient of velocity (CV_i) in the context of the third (CV_3) and the ninth day (CV_9) of germination using water extraction of weeds (concentration of 4.0%) (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

Calculation of this indicator within the studied weed species confirmed our conclusions regarding the difference in the expression of allelopathic effect depending on the variant of seed germination. For most weed species, this difference corresponded to the transition to the lowest value interval, except for species such as *Setaria glauca* L. (5), *Cynodon dactylon* (L.) Pers. (10), *Capsella bursa–pastoris* L. (1), *Cirsium arvense* (L.) Scopoli (9), for which the difference is determined in two gradations. It should be noted that these species, based on the results of our previous studies (Tsytsiura, 2020), belong to the herbological forms with a dominant vitality tactics in all tiers of high–altitude plant development, in particular in the phase of seedlings – the formation of the rosette in the oilseed radish (BBCH 14–20), the middle tier in the phase of stem formation – beginning of budding of oilseed radish plants (BBCH 26–50).

During the maturation period (BBCH 83–89), such species as *Setaria glauca* L. and *Cirsium arvense* (L.) Scopoli occupy the dominant upper tier, which classifies them as being associated with development in relation to the crop and explains the nature of OAP formation, as described in certain conclusions of other studies (Duke, 2015; Carvalho et al., 2019). It should be noted that the provided grouping results (Table 4.10) indicate another important pattern. The highest OAP values with respect to the indicator of the oilseed radish laboratory germination were noted for the species most common in the agrophytocoenosises of this crop in the research region, as well as among weeds of similar species. In fact, the first group includes all types of weeds with the OAP range of 0.56–0.70, excluding *Portulaca oleracea* L. (47), *Aethusa cynapium* L. (76), *Plantago major* L. (38), *Cuscuta campestris* Yuncker (71), *Polytrichum commune* L. (33), the presence of which in the oilseed radish cenosis is minimal. The second group should include species from the same interval, covering both regular weeds and culturally related species, which are studied in the self–seeding or fallen format – *Brassica napus* L. (25), *Rocket-cress* Brown (26), *Sinapis arvensis* L. (34), *Brassica campestris* (L.) Janchen (14), *Raphanus raphanistrum* L. (20). At the same time, the maximum OAP value at germination on both substrates was noted in the variant of using oilseed radish extracts (*Raphanus sativus* L. var. *oleiformis* Pers. (15)) – 0.68–0.72, which emphasizes the high degree of allelopathic self–incompatibility of the species at the stage of germination, and it's confirmed in studies conducted by Brown and Morra (1996), Norsworthy (2003), Haramoto (2004), Lawley et al. (2012).

Thus, the efficiency of the oilseed radish application with respect to plant species from the cruciferous family and species with OAP above 0.60 is determined by the seeding rate and the level of potential contamination of the field. The majority of plant species under study with the OAP interval of 0.26–0.50 have a low and average frequency level of occurrence in the agrophytocoenosis of oilseed radish, which rationally correlates with the theory of remote allelopathy for species that belong to different levels of introduction and vitality tactics of their existence (Novak et al., 2018) (for example, *Achillea millefolium* L. (60), *Centaurea cyanus* L. (27), *Erigeron canadensis* L. (6)), and with a low level of allelopathic competition due to the formation of morphotypes typical for terrestrial or lower tier in the vertical structure of the oilseed radish cenosis (for example, *Stellaria media*

(L.) Vill. (4), *Poa annua* L. (63), *Lepidium campestre* (L.) Brown (45)). As for such plants, the allelopathic competition with oilseed radish in the same phase is low, which makes it possible to apply it as a biological method of controlling the number and prevalence of these weed species at appropriate technological parameters of sowing. Such a conclusion of our research differs from the classical recommendations on the principles of selection of green manure crops for biological control of the field contamination level (Hoffman et al., 2006, Hodgdon et al., 2016) and allows the effective application of oilseed radish depending on the type of species contamination of the field at the beginning of vegetation–growth of the latter.

Table 4.10

Grouping of weed species according to their allelopathic potential (OAP) of impact oilseed radish seed germination (BBCH 01–05) (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

OAP interval	Weed species, which belong to the interval group		Number of species in the group	
	water substrate	soil substrate	water substrate	soil substrate
1	2	3	4	5
0.26–0.30	–	*Lepidium campestre* (L.) Brown, *Poa annua* L.	–	2
0.30–0.35	*Erigeron canadensis* L., *Lepidium campestre* (L.) Brown, *Poa annua* L.	*Stellaria media* (L.) Vill., *Setaria glauca* L., *Erigeron canadensis* L., *Carduus acanthoides* L., *Centaurea cyanus* L., *Lactuca serriola* L., *Achillea millefolium* L.	3	7
0.36–0.40	*Stellaria media* (L.) Vill., *Centaurea cyanus* L., *Lactuca serriola* L., *Achillea millefolium* L., *Erodium cicutarium* (L.) L'Héritier	*Cynodon dactylon* (L.) Pers., *Taraxacum officinale* Weber, *Lepidium ruderale* L., *Daucus carota* L., *Lamium purpureum* L., *Spergula vulgaris* L., *Erodium cicutarium* (L.) L'Héritier, *Panicum capillare* L.	5	8

(End of Table 4.10)

1	2	3	4	5
0.41–0.45	*Setaria glauca* L., *Carduus acanthoides* L., *Taraxacum officinale* Weber, *Lepidium ruderale* L., *Daucus carota* L., *Bromus secalinus* L., *Lamium purpureum* L., *Veronica hederifolia* L., *Spergula vulgaris* L., *Panicum capillare* L.	*Polygonum lapathifolium* (L.) Delarbre, *Artemisia vulgaris* L., *Rumex confertus* Willdenow, *Arctium lappa* L., *Eryngium campestre* L., *Polygonum aviculare* L., *Bromus secalinus* L., *Veronica hederifolia* L., *Crepis tectorum* L., *Lamium amplexicaule* L.	10	10
0.46–0.50	*Cynodon dactylon* (L.) Pers., *Artemisia vulgaris* L., *Berteroa incana* (L.) de Candolle, *Rumex confertus* Willdenow, *Arctium lappa* L., *Eryngium campestre* L., *Polygonum aviculare* L., *Crepis tectorum* L., *Lamium amplexicaule* L., *Digitaria ischaemum* (Schreber) Muhlenberg, *Rumex acetosella* L., *Echium vulgare* L., *Bunias orientalis* L.	*Capsella bursa–pastoris* L., *Galium aparine* L., *Ambrosia artemisiifolia* L., *Thlaspi arvense* L., *Echinochloa crus–galli* (L.) P.Beauv., *Berteroa incana* (L.) de Candolle, *Artemisia absinthium* L., *Setaria viridis* (L.) Palisot de Beauvois, *Descurainia Sophia* (L.) Prantl, *Avena fatua* L., *Digitaria ischaemum* (Schreber) Muhlenberg, *Senecio vernalis* (Waldstein & Kitaibel) Alexander, *Rumex acetosella* L., *Echium vulgare* L., *Bunias orientalis* L.	13	15
0.51–0.55	*Ambrosia artemisiifolia* L., *Thlaspi arvense* L., *Polygonum lapathifolium* (L.) Delarbre, *Artemisia absinthium* L., *Setaria viridis* (L.) Palisot de Beauvois, *Descurainia Sophia* (L.) Prantl, *Cichorium intybus* L., *Avena fatua* L., *Chondrilla juncea* L., *Senecio vernalis* (Waldstein & Kitaibel) Alexander, *Plantago lanceolata* L., *Solanum nigrum* L.	*Cirsium arvense* (L.) Scopoli, *Sonchus arvensis* L., *Brassica napus* L., *Lepidium draba* L., *Cichorium intybus* L., *Chondrilla juncea* L., *Cyclachaena xanthiifolia* Nuttall, *Plantago lanceolata* L., *Sisymbrium Loeselii* L., *Aethusa cynapium* L., *Solanum nigrum* L.	12	11

(End of Table 4.10)

1	2	3	4	5
0.56–0.60	*Capsella bursa–pastoris* L., *Galium aparine* L., *Echinochloa crus–galli* (L.) P.Beauv., *Agropyron repens* (L.) Gould, *Sonchus arvensis* L., *Brassica napus* L., *Rocket-cress* Brown, *Equisetum arvense* L., *Lepidium draba* L., *Portulaca oleracea* L., *Cyclachaena xanthiifolia* Nuttall, *Sisymbrium Loeselii* L., *Onopordon acanthium* L., *Polygonum convolvulus* (L.) Löve, *Aethusa cynapium* L.	*Brassica campestris* (L.) Janchen, *Agropyron repens* (L.) Gould, *Tripleurospermum maritimum* (L.) Koch, *Galinsoga parviflora* Cavanilles, *Convolvulus arvensis* L., *Rocket-cress* Brown, *Polytrichum commune* L., *Equisetum arvense* L., *Consolida regalis* Gray, *Sinapis alba* L., *Portulaca oleracea* L., *Fumaria officinalis* L., *Amaranthus blitoides* Watson, *Onopordon acanthium* L., *Polygonum convolvulus* (L.) Löve	15	15
0.61–0.65	*Cirsium arvense* (L.) Scopoli, *Tripleurospermum maritimum* (L.) Koch, *Galinsoga parviflora* Cavanilles, *Convolvulus arvensis* L., *Polytrichum commune* L., *Sinapis arvensis* L., *Consolida regalis* Gray, *Plantago major* L., *Sinapis alba* L., *Fumaria officinalis* L., *Amaranthus blitoides* Watson	*Papaver rhoeas* L., *Amaranthus retroflexus* L., *Raphanus raphanistrum* L., *Chenopodium album* L., *Sinapis arvensis* L., *Plantago major* L., *Acroptilon repens* (L.) de Candolle	11	7
0.66–0.70	*Papaver rhoeas* L., *Brassica campestris* (L.) Janchen, *Amaranthus retroflexus* L., *Raphanus raphanistrum* L., *Chenopodium album* L., *Acroptilon repens* (L.) de Candolle, *Cuscuta campestris* Yuncker	*Raphanus sativus* L. var. *oleiformis* Pers., *Cuscuta campestris* Yuncker	7	2
0.71–0.75	*Raphanus sativus* L. var. *oleiformis* Pers.	–	1	–

Certain peculiarities of influence on germination have stelting (*Convolvulus arvensis* L. (24), *Polygonum convolvulus* (L.) Löve (74) and parasitic species of weeds (*Cuscuta campestris* Yuncker (71)), which emphasizes their biological versatility in relation to the possibility of growth and development with the coverage of all tiers of plants and aggressive biology in relation to other plant species for parasitic studied forms, which is confirmed by studies of Marinov–Serafimov et al. (2017).

It is pointed out (Iqbal and Fry, 2012; Fragasso et al., 2013; Golubinova and Ilieva, 2014; Gfeller et al., 2018) that the allelopathic effect of plant extracts affects not only the indicators of seed germination and the indicator formation speed, but also the growth processes of plants. The intensity of this impact depends on the phenological phase of application of such substances. According to Jabran et al. (2015) and Marinov–Serafimov and Golubinova (2015), the assessment of allelopathic effects in plant relationships must be accompanied by an analysis of growth processes in the system of relevant indicators and growth correlations, which will give a complete picture of the target effect of the relevant plant extracts on growth and development of the test object. Given these statements, during the second experiment in the format of oilseed radish cultivation on the soil substrate with the addition of extracts of the studied plant species, we analyzed a number of indicators related to the analysis of growth rates. Significant differences for the majority of comparison pairs according to Tukey's criterion in terms of the influence of allelopathic extracts on the growth and development of oilseed radish plants at the initial stages of vegetation (BBCH 01–12) have been determined. The data of such research is presented in Table 4.11 for the extract concentrations in the range of 4.0–1.0%, and for some variants of the experiment in Figure 4.12. It was found that the impact of extracts on growth processes had a species–specific nature with differences in the impact on the root system and stem (above–ground) parts, which is evidenced by the ratio between the formation of dry matter of the stem and root systems in the DWR index format and its comparison with the control version, as well as the value of Coefficient of allometry (CA) in the context of the studied plant species. Overall, the evaluation of the above ratios between morphological parameters of the aboveground and root systems is an important factor in allelopathic analysis, since each plant species is characterized by a certain ratio index between stem and root system development. Certainly, this ratio changes depending on vegetation conditions, soil and climate parameters, but in certain intervals it is relatively constant. This factor in the allelopathic analysis is pointed out in the studies of Grodzinsky (1965), Macías et al., (2007), Duke (2015). This criterion adequately reflects the intensity and specificity of growth processes of plants, distributing them into certain types. At the same time, the allelopathic pressure between species is higher if the growth ratio of above–ground and underground parts of the plant is of the same type, and the biological and chemical influence of the allelopathic substances will affect this ratio (Rice, 1984).

In studies, such processes have been confirmed. Extracts of different types of weeds had different impact both on the amount of alometric and on the amount of weight (by dry matter accumulation index) coefficients in comparison to control. Even in the absence of significant morphological differences (see Fig. 4.12) between the concentration variants of the applicable water extract, there is a general decrease in the area of seed lobe, a decrease in the diameter of hypocotyl, as well as some deformation of the above–ground part. As for the root systems, certain morphological peculiarities of development have also been determined for the test plants – from the general elongation of the root system without explicit lateral branching (variant of *Sonchus arvensis* L. (19)) to intensive radial branching with minimal linear elongation (variant of *Erigeron canadensis* L. (6)).

As a result, we found that reducing the concentration of water extract from weed plants from 4.0% to 1.0% reduces the disparity between the ratio of stem and root parts coming closer to the control variant indicator and provides the formation of greater above–ground mass and corresponding dry matter value. Such dynamics of ratios indicates the dominant influence of extracts on the formation of the root system, and for species with high allelopathic potential and associated intensive impact both on the root and stem parts. But with a generally defined tendency of changes in indicators, there are also relevant exceptions.

Table 4.11

Allelopathic effect of water extracts from weeds on the oilseed radish growing processes (*Raphanus sativus* L. var. *oleiformis* Pers.) (when germinating on a soil substrate) (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

CVN	Length, mm				Seedling												GRI		CA		DWR	
	root		stem		DDI		TI (%)		μ 10^{-2}		GI (%)		SVI		RI							
	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0	30.2	30.2	80.2	80.2	–	–	1.00	1.00	–	–	–	–	98.5	99.1	–	–	33.5	33.8	2.7	2.7	5,1	5,1
1	10.5	17.0	64.2	71.0	–4.8	–8.3	0.68	0.80	–2,2	–1,3	12.8	40.6	12.6	51.7	–0.32	–0.20	2.8	14.1	6.1	4.2	7.1	10.2
2	13.8	23.9	44.9	72.7	–3.0	–14.1	0.53	0.88	–3,5	–0,7	9.2	52.3	9.1	55.8	–0.47	–0.12	4.7	19.0	3.3	3.0	4.2	7.1
3	10.9	15.9	41.4	58.3	–2.5	–4.7	0.47	0.67	–4,1	–2,2	10.4	37.9	10.3	41.8	–0.53	–0.33	5.1	15.3	3.8	3.7	5.3	8.3
4	8.0	13.4	42.8	56.7	–2.4	–4.1	0.46	0.64	–4,3	–2,5	14.8	53.6	14.6	58.3	–0.54	–0.36	5.4	19.7	5.3	4.2	6.6	9.5
5	13.6	25.4	34.0	61.0	–2.2	–7.7	0.43	0.78	–4,7	–1,4	15.7	56.7	15.5	62.7	–0.57	–0.22	13.0	30.2	2.5	2.4	2.9	5.4
6	8.2	14.6	40.8	60.1	–2.3	–4.8	0.44	0.68	–4,5	–2,2	20.7	54.3	20.4	58.2	–0.56	–0.32	8.4	18.9	5.0	4.1	6.3	9.3
7	7.7	16.3	36.9	54.0	–2.1	–4.2	0.40	0.64	–5,0	–2,5	15.2	42.9	14.9	48.8	–0.60	–0.36	7.0	20.9	4.8	3.3	5.3	7.5
8	10.0	20.5	35.5	58.4	–2.1	–5.6	0.41	0.72	–4,9	–1,9	10.9	37.9	10.7	43.2	–0.59	–0.28	6.6	19.2	3.5	2.8	4.9	6.4
9	11.0	15.4	29.4	46.9	–1.9	–3.3	0.37	0.56	–5,6	–3,2	6.2	22.7	6.1	27.8	–0.63	–0.44	5.7	14.6	2.7	3.1	3.9	6.9
10	5.9	20.1	25.2	40.5	–1.5	–3.1	0.28	0.55	–7,0	–3,3	6.1	39.8	6.0	45.0	–0.72	–0.45	4.5	36.9	4.3	2.0	3.6	4.6
11	6.9	13.9	40.7	54.8	–2.2	–4.0	0.43	0.62	–4,7	–2,6	6.7	35.1	6.6	45.2	–0.57	–0.38	2.4	16.7	5.9	3.9	6.2	8.9
12	13.9	24.8	30.4	53.1	–2.1	–5.4	0.40	0.71	–5,1	–1,9	9.4	37.7	9.2	47.0	–0.60	–0.29	9.5	28.1	2.2	2.1	2.9	4.9
13	15.9	26.0	31.9	55.3	–2.2	–6.1	0.43	0.74	–4,7	–1,7	5.3	23.5	5.2	28.9	–0.57	–0.26	5.4	16.7	2.0	2.1	2.7	4.8
14	10.1	13.6	36.5	48.9	–2.2	–3.3	0.42	0.57	–4,8	–3,2	3.7	23.5	3.6	26.6	–0.58	–0.43	2.2	11.9	3.6	3.6	5.3	8.1
15	9.6	15,7	23.1	41.8	–2.0	–4.3	0.39	0.65	–5,3	–2,4	2.3	24.3	2.2	28.3	–0.68	–0.47	2.7	19.9	2.4	2.7	2.4	4.5
16	11.4	18.2	41.3	46.4	–2.5	–3.5	0.48	0.58	–4,1	–3,0	6.9	26.6	6.8	28.8	–0.52	–0.42	3.5	17.4	3.6	2.6	5.2	5.8
17	8.0	14.0	37.2	45.7	–2.1	–3.1	0.41	0.54	–5,0	–3,4	3.2	19.6	3.1	21.3	–0.59	–0.46	1.5	10.9	4.7	3.3	5.7	7.4
18	14.2	24.4	24.5	37.9	–1.8	–3.3	0.35	0.56	–5,8	–3,2	8.4	47.1	8.2	49.6	–0.65	–0.44	12.3	51.3	1.7	1.6	2.1	3.5
19	17.6	27.0	47.0	57.9	–3.5	–7.2	0.59	0.77	–3,0	–1,5	5.6	48.5	5.6	51.3	–0.41	–0.23	3.2	28.2	2.7	2.1	3.8	4.8
20	12.0	23.2	40.5	56.3	–2.5	–5.7	0.48	0.72	–4,1	–1,8	2.7	30.0	2.7	32.4	–0.52	–0.28	1.5	16.8	3.4	2.4	3.9	5.5
21	18.9	28.1	27.8	43.9	–2.2	–4.4	0.42	0.65	–4,8	–2,4	5.5	29.4	5.4	31.4	–0.58	–0.35	7.8	27.9	1.5	1.6	2.1	3.5
22	10.2	27.9	21.6	37.2	–1.5	–3.6	0.29	0.59	–6,9	–2,9	4.5	22.6	4.4	26.4	–0.71	–0.41	6.6	30.4	2.1	1.3	2.5	3.0

(End of Table 4.11)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
23	11.7	23.9	32.3	56.4	–2.0	–5.9	0.40	0.73	–5,1	–1,8	4.1	23.3	4.0	25.9	–0.60	–0.27	3.3	13.7	2.8	2.4	2.7	5.4
24	15.8	18.0	31.3	53.4	–2.2	–4.3	0.43	0.65	–4,7	–2,4	5.6	29.2	5.5	31.1	–0.57	–0.35	5.9	14.7	2.0	3.0	3.2	6.7
25	7.8	12.1	22.0	42.1	–1.4	–2.6	0.27	0.49	–7,3	–3,9	4.2	25.3	4.1	26.9	–0.73	–0.51	4.9	14.3	2.8	3.5	3.8	7.8
26	6.9	22.9	31.0	39.4	–1.8	–3.3	0.34	0.57	–5,9	–3,2	6.0	24.1	5.9	25.4	–0.66	–0.43	3.5	23.7	4.5	1.7	4.2	3.9
27	8.1	15.9	39.3	46.8	–2.2	–3.3	0.43	0.57	–4,7	–3,1	16.1	42.0	15.9	44.1	–0.57	–0.43	6.9	23.9	4.8	2.9	6.1	6.7
28	11.1	17.7	32.6	43.2	–2.0	–3.2	0.40	0.55	–5,1	–3,3	8.8	35.8	8.7	38.0	–0.60	–0.45	6.8	25.6	2.9	2.4	3.8	5.5
29	15.2	23.0	31.2	56.3	–2.2	–5.7	0.42	0.72	–4,8	–1,8	10.1	42.9	9.9	45.9	–0.58	–0.28	10.4	23.7	2.1	2.4	3.1	5.5
30	11.4	20.2	41.8	55.1	–2.6	–4.9	0.48	0.68	–4,1	–2,1	6.8	42.5	6.7	46.7	–0.52	–0.32	3.4	22.7	3.7	2.7	4.5	6.2
31	14.2	23.9	40.9	62.9	–2.7	–7.8	0.50	0.79	–3,9	–1,3	6.1	66.3	6.0	69.8	–0.50	–0.21	3.8	30.6	2.9	2.6	3.7	5.9
32	12.0	21.0	40.5	50.5	–2.5	–4.3	0.48	0.65	–4,1	–2,4	10.5	35.9	10.3	38.4	–0.52	–0.35	5.8	22.4	3.4	2.4	4.5	5.4
33	11.1	18.8	39.9	54.1	–2.4	–4.5	0.46	0.66	–4,3	–2,3	5.9	26.9	5.8	28.7	–0.54	–0.34	3.2	13.7	3.6	2.9	4.8	6.5
34	9.4	18.7	36.7	51.8	–2.2	–4.2	0.42	0.64	–4,8	–2,5	1.8	31.3	1.8	33.3	–0.58	–0.36	1.0	17.0	3.9	2.8	4.3	6.3
35	13.2	26.9	48.3	60.4	–3.2	–8.0	0.56	0.79	–3,3	–1,3	7.4	61.9	7.3	64.5	–0.44	–0.21	3.2	32.9	3.7	2.2	4.0	5.1
36	11.8	20.3	32.5	40.3	–2.1	–3.1	0.40	0.55	–5,1	–3,3	2.2	31.0	2.1	31.0	–0.60	–0.45	1.7	25.8	2.7	2.0	3.5	4.5
37	12.0	20.3	34.7	48.9	–2.2	–4.0	0.42	0.63	–4,8	–2,6	6.1	22.0	6.0	24.1	–0.58	–0.37	4.4	14.4	2.9	2.4	3.5	5.5
38	14.8	22.4	42.2	58.9	–2.8	–6.1	0.52	0.74	–3,7	–1,7	5.2	27.5	5.1	29.1	–0.48	–0.26	3.1	13.6	2.8	2.6	3.9	5.9
39	13.1	26.0	29.2	46.6	–2.0	–4.5	0.38	0.66	–5,3	–2,3	5.4	52.8	5.3	54.6	–0.62	–0.34	5.6	42.0	2.2	1.8	2.7	4.1
40	11.3	23.7	37.6	51.4	–2.3	–4.9	0.44	0.68	–4,5	–2,1	6.9	57.6	6.7	60.1	–0.56	–0.32	4.1	36.9	3.3	2.2	3.8	4.9
41	7.9	16.0	42.8	55.7	–2.4	–4.4	0.46	0.65	–4,3	–2,4	13.2	45.2	13.0	49.9	–0.54	–0.35	4.7	20.1	5.4	3.5	6.2	7.9
42	7.3	14.2	22.9	40.6	–1.4	–2.7	0.27	0.50	–7,2	–3,9	3.2	20.7	3.2	21.8	–0.73	–0.50	3.4	13.9	3.1	2.9	3.5	6.5
43	5.8	11.5	29.3	39.6	–1.6	–2.4	0.32	0.46	–6,4	–4,3	4.8	23.5	4.8	24.8	–0.68	–0.54	2.7	14.1	5.1	3.4	5.2	7.8
44	10.0	16.2	29.8	40.1	–1.8	–2.8	0.36	0.51	–5,7	–3,7	9.1	43.5	9.0	45.3	–0.64	–0.49	7.6	32.5	3.0	2.5	3.9	5.6
45	12.0	20.8	35.1	56.6	–2.2	–5.3	0.43	0.70	–4,7	–2,0	17.0	63.6	16.8	66.3	–0.57	–0.30	12.2	31.5	2.9	2.7	3.8	6.2
46	10.3	19.1	31.2	54.8	–1.9	–4.7	0.38	0.67	–5,4	–2,2	6.7	50.1	6.6	52.3	–0.62	–0.33	5.3	24.7	3.0	2.9	3.8	6.5
47	12.0	22.3	27.2	35.2	–1.8	–2.9	0.36	0.52	–5,7	–3,6	3.1	27.2	3.1	28.8	–0.64	–0.48	3.4	31.7	2.3	1.6	2.8	3.6
48	8.1	17.4	21.6	38.8	–1.4	–2.8	0.27	0.51	–7,3	–3,7	2.7	22.7	2.6	22.4	–0.73	–0.49	3.3	17.9	2.7	2.2	2.7	5.0
49	10.1	18.1	24.3	36.5	–1.6	–2.7	0.31	0.49	–6,5	–3,9	4.5	31.7	4.4	33.4	–0.69	–0.51	5.4	30.4	2.4	2.0	3.5	4.6
50	14.4	19.9	31.8	44.1	–2.2	–3.4	0.42	0.58	–4,8	–3,0	9.3	26.5	9.1	28.4	–0.58	–0.42	8.9	20.1	2.2	2.2	3.4	5.0
51	11.1	21.7	26.9	38.3	–1.8	–3.1	0.34	0.54	–5,9	–3,4	6.9	31.9	6.8	33.5	–0.66	–0.46	7.3	31.6	2.4	1.8	2.7	4.0
52	14.8	16.9	32.2	42.9	–2.2	–3.1	0.43	0.54	–4,7	–3,4	11.3	39.9	11.1	39.9	–0.57	–0.46	10.8	26.3	2.2	2.5	3.9	5.7
53	11.1	19.2	27.3	45.0	–1.8	–3.5	0.35	0.58	–5,9	–3,0	8.3	43.5	8.2	45.7	–0.65	–0.42	8.7	30.5	2.5	2.3	3.4	5.3

(End of Table 4.11)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
54	13.7	17.8	24.2	45.1	–1.8	–3.3	0.34	0.57	–5,9	–3,1	9.8	38.4	9.7	40.0	–0.66	–0.43	14.5	25.1	1.8	2.5	2.6	5.7
55	9.7	15.9	33.7	47.2	–2.0	–3.4	0.39	0.57	–5,2	–3,1	6.7	30.5	6.6	32.1	–0.61	–0.43	4.4	17.1	3.5	3.0	4.3	6.7
56	10.3	17.2	36.7	54.8	–2.2	–4.4	0.42	0.65	–4,8	–2,4	9.3	44.4	9.2	44.5	–0.58	–0.35	5.5	19.3	3.6	3.2	4.0	7.2
57	11.4	18.4	37.4	59.1	–2.3	–5.3	0.44	0.70	–4,5	–2,0	11.8	44.4	11.6	44.6	–0.56	–0.30	7.2	17.9	3.3	3.2	4.2	7.3
58	8.1	13.1	25.3	38.7	–1.6	–2.5	0.30	0.47	–6,6	–4,2	4.3	25.1	4.2	26.3	–0.70	–0.53	4.1	17.2	3.1	3.0	4.2	6.7
59	8.8	16.8	30.1	40.1	–1.8	–2.8	0.35	0.52	–5,8	–3,7	7.4	31.9	7.2	33.3	–0.65	–0.48	5.4	24.6	3.4	2.4	3.5	5.4
60	10.7	19.1	45.2	59.2	–2.8	–5.5	0.51	0.71	–3,8	–1,9	15.8	59.3	15.5	61.4	–0.49	–0.29	6.6	25.3	4.2	3.1	5.5	7.0
61	8.3	15.4	33.2	41.4	–1.9	–2.8	0.38	0.51	–5,4	–3,7	6.4	31.3	6.3	31.1	–0.62	–0.49	3.8	20.4	4.0	2.7	5.1	6.1
62	11.2	19.4	41.8	60.6	–2.6	–5.8	0.48	0.72	–4,1	–1,8	13.2	56.1	13.0	57.8	–0.52	–0.28	6.6	23.1	3.7	3.1	4.7	7.1
63	14.0	20.1	35.0	45.7	–2.3	–3.6	0.44	0.60	–4,5	–2,9	17.7	51.2	17.4	52.9	–0.56	–0.40	14.3	35.4	2.5	2.3	3.6	5.1
64	7.4	14.3	25.2	42.4	–1.5	–2.8	0.30	0.51	–6,8	–3,7	3.0	22.4	3.0	22.4	–0.70	–0.49	2.7	13.4	3.4	3.0	4.3	6.7
65	14.7	20.6	41.5	51.2	–2.8	–4.4	0.51	0.65	–3,8	–2,4	8.8	33.9	8.7	36.0	–0.49	–0.35	5.5	20.1	2.8	2.5	3.7	5.6
66	6.7	14.1	21.4	31.5	–1.4	–2.1	0.25	0.41	–7,6	–4,9	1.9	14.5	1.9	15.3	–0.75	–0.59	2.1	15.1	3.2	2.2	3.8	5.0
67	12.2	18.5	39.3	54.2	–2.5	–4.5	0.47	0.66	–4,2	–2,3	15.5	52.3	15.2	50.7	–0.53	–0.34	9.2	23.8	3.2	2.9	4.0	6.6
68	12.4	20.5	38.8	50.7	–2.4	–4.3	0.46	0.65	–4,3	–2,4	14.5	48.1	14.2	50.4	–0.54	–0.35	8.9	28.6	3.1	2.5	3.8	5.6
69	13.4	20.1	35.9	42.4	–2.3	–3.3	0.45	0.57	–4,5	–3,2	6.9	38.1	6.8	39.9	–0.55	–0.43	5.1	30.2	2.7	2.1	3.8	4.8
70	8.3	15.2	40.4	56.7	–2.3	–4.4	0.44	0.65	–4,5	–2,4	6.2	33.5	6.1	35.4	–0.56	–0.35	2.6	13.2	4.9	3.7	5.7	8.4
71	6.7	14.4	20.7	37.0	–1.3	–2.5	0.25	0.47	–7,7	–4,3	1.6	14.7	1.6	14.6	–0.75	–0.53	1.9	11.0	3.1	2.6	3.6	5.8
72	7.7	16.4	30.6	39.5	–1.8	–2.8	0.35	0.51	–5,9	–3,8	4.6	24.3	4.5	25.3	–0.65	–0.49	3.0	18.8	4.0	2.4	4.3	5.4
73	11.1	17.7	33.5	50.0	–2.1	–3.8	0.40	0.61	–5,0	–2,7	8.3	38.2	8.2	40.4	–0.60	–0.39	6.1	21.0	3.0	2.8	3.8	6.4
74	12.0	16.1	27.8	42.6	–1.8	–3.0	0.36	0.53	–5,7	–3,5	4.0	23.7	3.9	25.4	–0.64	–0.47	4.2	16.3	2.3	2.6	3.9	6.0
75	8.8	15.1	42.2	57.8	–2.4	–4.5	0.46	0.66	–4,3	–2,3	7.9	43.6	7.8	45.6	–0.54	–0.34	3.2	16.4	4.8	3.8	6.3	8.7
76	7.4	17.7	31.4	55.5	–1.8	–4.6	0.35	0.66	–5,8	–2,3	6.1	29.7	6.0	35.8	–0.65	–0.34	3.6	15.5	4.3	3.1	5.2	7.1
77	8.6	18.1	41.9	59.3	–2.4	–5.3	0.46	0.70	–4,3	–2,0	6.6	38.3	6.5	38.5	–0.54	–0.30	2.6	15.2	4.9	3.3	5.4	7.4
SSD (LSD test)	0.9	1.1	1.3	1.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Tukey's test: total number of comparable comparison pairs 3003, number of comparison pairs that were not included in 95% confidence interval (p_{adj}=0.516–1.000) 689 (22.94% of values that do not differ significantly)																						

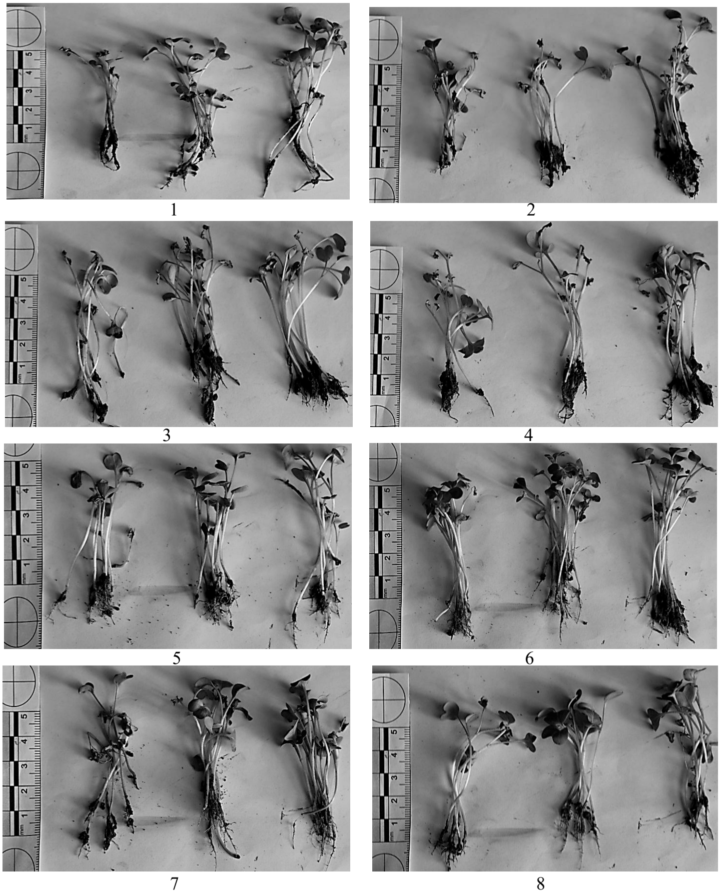


Figure 4.12 – Oilseed radish plants when grown in the soil substrate, obtained in the variants of three water extracts of weeds at a successive concentration of the solution (from left to right) 4.0, 2.0 and 1.0% (1 – *Berteroa incana* (L.) de Candolle (29); 2 – *Cynodon dactylon* (L.) Pers. (10); 3 – *Echinochloa crus–galli* (L.) P. Beauv. (11); 4 – *Polygonum lapathifolium* (L.) Delarbre (12); 5 – *Lepidium campestre* (L.) Brown (45); 6 – *Polygonum aviculare* L. (46); 7 – *Portulaca oleracea* L. (47); 8 – *Fumaria officinalis* L. (48)) (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

Thus, the growth of the CA indicator at a decrease in concentration was noted under the influence of such species as *Cirsium arvense* (L.) Scopoli (9), *Cirsium arvense* (L.) Scopoli (13), *Convolvulus arvensis* L. (24), *Brassica napus* L. (25), *Berteroa incana* (L.) de Candolle (29), *Bromus secalinus* L. (52), *Veronica hederifolia* L. (54), *Polygonum convolvulus* (L.) Löve (74). Equal values of the CA indicator for both concentrations, which testifies to the unidirectional effect of influence on growth processes of aboveground and underground parts was noted under the influence of such species as *Brassica campestris* (L.) Janchen (14), *Taraxacum officinale* Weber (18), *Tripleurospermum maritimum* (L.) Koch (21), *Cichorium intybus* L. (50), *Lamium amplexicaule* L. (57). According to Reigosa et al. (2006), Kunz et al. (2016), such influence nature indicates an appropriate level of physiological activity of the extract substances in relation to the test object.

A grouping informative indicator that combines such intermediate calculated indices as DDI, SVI, CA, TI, μ is index of plant development (GI). According to Marinov–Serafimov et al. (2013), it is a certain alternative to the overall allelopathic potential indicator (OAP). In our studies, this has been effectively confirmed. Thus, variants with low GI values (in the range of 3–23% depending on the concentration of water extract) have the highest estimated OAP gradation (Table 4.12) according to the Smith scale (2013) and the grouping performed (Table 4.13).

It should be noted that the OAP indicator was different for the root system and stems of oilseed radish plants under the action of the corresponding weed extract. It confirms our earlier conclusions about the CA indicator in the system of evaluating the allelopathic activity of the studied plant species, predetermining the need to calculate the integral (average) OAP indicator.

The obtained data allowed us to divide the whole totality of analyzed plant species and divide them by allelopathic activity. In various scientific researches (Rice, 1984; Williamson and Richardson, 1988; Izzet et al., 2004; Zimdahl, 2004, 2018; Kader et al., 2005; Yurchak, 2005; John et al., 2006; Anwar et al., 2013; Smith, 2013; Brust et al., 2014; Syed et al., 2014; Bakhshayeshan-Agdam et al., 2015; Rueda-Ayala et al., 2015; Boydston and Al–Khatib, 2016; Marinov-Serafimov et al., 2017; Arroyo et al., 2018), it was noted that the OAP indicator is a measure of the overall allelopathic effect of relationships in the system weed–tester plant, and in the variant of determining the indicators of allelopathic pressure by laboratory germination indicators and initial growth, showing the level of competitiveness of the tester plant in relation to a particular type of weed ignoring the rate of vegetative growth of the tester, the level of its vitality tactics and other factors. But it clearly divides species by thresholds values of important starting competition, which determines the subsequent success of the formation of agrophytocoenosis of any crop plant.

According to the proposed gradation of Smitha (2013) and the assessments of other scientists (Grodzinsky, 1965; Ivanov, 1973; Rabotnov, 1982; Rice, 1984; Matveev, 1994; Inderjit, 1999; Syed et al., 2014), in terms of the ratio of weeds with the OAP level above and below 5.0, oilseed radish can be attributed to species with high herbal competition potential, where this indicator was 0.75.

This grouping confirms our previous studies on the peculiarities of weed cenosis formation in the general agrophytocoenosis of oilseed radish (Tsytsiura, 2020), since the majority of weed species, which are classified in the category with the OAP level more than 0.5, are dominant in different periods of growth and development of oilseed radish plants in the context of different cenosis tiers. In particular, these species include *Cirsium arvense* (L.) Scopoli, *Echinochloa crus–galli* (L.) P. Beauv., *Chenopodium album* L., *Polygonum convolvulus* (L.) Löve, *Amaranthus retroflexus* L., *Agropyron repens* (L.) de Candolle, *Galinsoga parviflora* Cavanilles. The species botanically similar to the oilseed radish and the oilseed radish itself (*Raphanus sativus* L. var. *oleiformis* Pers., *Brassica napus* L., *Sinapis alba* L.) have also demonstrated a high allelopathic potential in relation to the impact on growth processes of the oilseed radish test plants. The highest OAP potential (0.64–0.66) was recorded for two weed species *Cuscuta campestris* Yuncker and *Acroptilon repens* (L.) de Candolle, although the prevalence of these species is low for oilseed radish agrophytocoenosises in the region.

Table 4.12

Overall allelopathic potential of weeds in relation to growth processes of oilseed radish plants (*Raphanus sativus* L. var. *oleiformis* Pers.) (for a concentration ratio of 4.0% to 1.0% when growing on the soil substrate) (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

CVN	Root		Stem		Seedling		Integrated OAP Score	CVN	Root		Stem		Seedling		Integrated OAP Score
	OAP	OAP Score	OAP	OAP Score	OAP	OAP Score			OAP	OAP Score	OAP	OAP Score	OAP	OAP Score	
1	0.54	HA	0.16	NA	0.26	MA	0.32	40	0.42	MA	0.45	MA	0.44	MA	0.43
2	0.37	MA	0.27	MA	0.30	MA	0.31	41	0.60	HA	0.39	MA	0.45	MA	0.48
3	0.56	HA	0.38	MA	0.43	MA	0.45	42	0.64	HA	0.60	HA	0.62	HA	0.62
4	0.64	HA	0.38	MA	0.45	MA	0.49	43	0.71	HA	0.57	HA	0.61	HA	0.63
5	0.35	MA	0.41	MA	0.39	MA	0.38	44	0.57	HA	0.56	HA	0.57	HA	0.57
6	0.62	HA	0.37	MA	0.44	MA	0.48	45	0.46	MA	0.43	MA	0.44	MA	0.44
7	0.60	HA	0.43	MA	0.48	MA	0.51	46	0.51	HA	0.46	MA	0.48	MA	0.48
8	0.49	MA	0.41	MA	0.44	MA	0.45	47	0.43	MA	0.61	HA	0.56	HA	0.53
9	0.56	HA	0.52	HA	0.53	HA	0.54	48	0.58	HA	0.62	HA	0.61	HA	0.60
10	0.57	HA	0.59	HA	0.58	HA	0.58	49	0.53	HA	0.62	HA	0.60	HA	0.58
11	0.65	HA	0.41	MA	0.47	MA	0.51	50	0.43	MA	0.53	HA	0.50	MA	0.49
12	0.36	MA	0.48	MA	0.45	MA	0.43	51	0.46	MA	0.59	HA	0.56	HA	0.54
13	0.31	MA	0.46	MA	0.42	MA	0.39	52	0.47	MA	0.53	HA	0.52	HA	0.51
14	0.61	HA	0.47	MA	0.51	HA	0.53	53	0.50	MA	0.55	HA	0.53	HA	0.53
15	0.58	HA	0.65	HA	0.62	HA	0.62	54	0.48	MA	0.57	HA	0.54	HA	0.53
16	0.51	HA	0.45	MA	0.47	MA	0.48	55	0.58	HA	0.50	HA	0.52	HA	0.53
17	0.64	HA	0.48	MA	0.53	HA	0.55	56	0.55	HA	0.43	MA	0.46	MA	0.48
18	0.36	MA	0.61	HA	0.54	HA	0.50	57	0.51	HA	0.40	MA	0.43	MA	0.44
19	0.26	MA	0.35	MA	0.32	MA	0.31	58	0.65	HA	0.60	HA	0.61	HA	0.62
20	0.42	MA	0.40	MA	0.40	MA	0.40	59	0.58	HA	0.56	HA	0.57	HA	0.57
21	0.22	NA	0.55	HA	0.46	MA	0.40	60	0.51	HA	0.35	MA	0.39	MA	0.42
22	0.37	MA	0.63	HA	0.56	HA	0.52	61	0.61	HA	0.53	HA	0.55	HA	0.57
23	0.47	HA	0.55	HA	0.51	HA	0.43	62	0.49	MA	0.36	MA	0.40	MA	0.42
24	0.44	MA	0.47	MA	0.46	MA	0.46	63	0.43	MA	0.50	MA	0.48	MA	0.47
25	0.67	HA	0.60	HA	0.62	HA	0.63	64	0.64	HA	0.58	HA	0.60	HA	0.60
26	0.50	MA	0.56	HA	0.55	HA	0.54	65	0.42	MA	0.42	MA	0.42	MA	0.42
27	0.60	HA	0.46	MA	0.50	MA	0.52	66	0.65	HA	0.67	HA	0.67	HA	0.66
28	0.52	HA	0.53	HA	0.53	HA	0.53	67	0.49	MA	0.42	MA	0.44	MA	0.45
29	0.37	MA	0.45	MA	0.43	MA	0.42	68	0.45	MA	0.44	MA	0.45	MA	0.45
30	0.48	MA	0.40	MA	0.42	MA	0.43	69	0.45	MA	0.51	HA	0.49	MA	0.48
31	0.37	MA	0.35	MA	0.36	MA	0.36	70	0.61	HA	0.39	MA	0.45	MA	0.49
32	0.45	MA	0.43	MA	0.44	MA	0.44	71	0.65	HA	0.64	HA	0.64	HA	0.64
33	0.50	MA	0.41	MA	0.44	MA	0.45	72	0.60	HA	0.56	HA	0.57	HA	0.58
34	0.53	HA	0.45	MA	0.47	MA	0.48	73	0.52	HA	0.48	MA	0.49	MA	0.50
35	0.34	MA	0.32	MA	0.33	MA	0.33	74	0.53	HA	0.56	HA	0.55	HA	0.55
36	0.47	MA	0.55	HA	0.53	HA	0.51	75	0.60	HA	0.38	MA	0.44	MA	0.47
37	0.46	MA	0.48	MA	0.47	MA	0.47	76	0.58	HA	0.46	MA	0.49	MA	0.51
38	0.38	MA	0.37	MA	0.37	MA	0.38	77	0.56	HA	0.37	MA	0.42	MA	0.45
39	0.35	MA	0.53	HA	0.48	MA	0.45	$SSD_{0.05}$	0.038		0.045		0.037		–

SSD – The smallest significant difference between the values according to LSD test for $p < 0.05$.

Table 4.13

Grouping of weed species according to their allelopathic potential (OAP) of oilseed radish impact on initial growth processes (BBCH 01–12) (Tsytsiura, 2022; Tsytsiura and Sampietro, 2024)

OAP interval	Weed species, which belong to the interval group	Numer of species in the group
0.30–0.35	*Capsella bursa–pastoris* L., *Galium aparine* L., *Sonchus arvensis* L., *Arctium lappa* L.	4
0.36–0.40	*Setaria glauca* L., *Papaver rhoeas* L., *Raphanus raphanistrum* L., *Tripleurospermum maritimum* (L.) Koch, *Plantago major* L., *Rumex confertus* Willdenow	6
0.41–0.45	*Ambrosia artemisiifolia* L., *Thlaspi arvense* L., *Polygonum lapathifolium* (L.) Delarbre, *Berteroa incana* (L.) de Candolle, *Artemisia absinthium* L., *Setaria viridis* (L.) Palisot de Beauvois, *Polytrichum commune* L., *Eryngium campestre* L., *Lepidium ruderale* L., *Lepidium campestre* (L.) Brown, *Lamium amplexicaule* L., *Achillea millefolium* L., *Spergula vulgaris* L., *Plantago lanceolata* L., *Erodium cicutarium* (L.) L'Héritier, *Panicum capillare* L., *Solanum nigrum* L.	18
0.46–0.50	*Stellaria media* (L.) Vill., *Erigeron canadensis* L., *Agropyron repens* (L.) Gould, *Taraxacum officinale* Weber, *Convolvulus arvensis* L., *Sinapis arvensis* L., *Consolida regalis* Gray, *Daucus carota* L., *Polygonum aviculare* L., *Cichorium intybus* L., *Crepis tectorum* L., *Poa annua* L., *Rumex acetosella* L., *Sisymbrium Loeselii* L., *Echium vulgare* L., *Bunias orientalis* L.	16
0.51–0.55	*Carduus acanthoides* L., *Cirsium arvense* (L.) Scopoli, *Echinochloa crus–galli* (L.) P. Beauv., *Brassica campestris* (L.) Janchen, *Chenopodium album* L., *Amaranthus retroflexus* L., *Galinsoga parviflora* Cavanilles, *Rocket-cress* Brown, *Centaurea cyanus* L., *Artemisia vulgaris* L., *Equisetum arvense* L., *Portulaca oleracea* L., *Avena fatua* L., *Bromus secalinus* L., *Lamium purpureum* L., *Veronica hederifolia* L., *Chondrilla juncea* L., *Polygonum convolvulus* (L.) Löve, *Aethusa cynapium* L.	18
0.56–0.60	*Cynodon dactylon* (L.) Pers., *Lactuca serriola* L., *Descurainia Sophia* (L.) Prantl, *Digitaria ischaemum* (Schreber) Muhlenberg, *Senecio vernalis* (Waldstein & Kitaibel) Alexander, *Amaranthus blitoides* Watson, *Onopordon acanthium* L., *Fumaria officinalis* L.	8
0.61–0.65	*Raphanus sativus* L. var. *oleiformis* Pers., *Brassica napus* L., *Sinapis alba* L., *Lepidium draba* L., *Cyclachaena xanthiifolia* Nuttall, *Cuscuta campestris* Yuncker	6
0.66–0.70	*Acroptilon repens* (L.) de Candolle	1

The data obtained is also confirmed by the level of allelopathic effect on other cultivated plants from a number of weed species under study, including the representatives of theConvolvulaceae (COVF) family in the studies of Marinov–Serafimov et al. (2017), Dadkhah and Rassam (2016); Brassicaceae (1CRUF) family species in the studies of Boydston and Hang (1995), Al–Khatib et al. (1997), Petersen et al. (2001), Turk and Tawaha (2003), Norsworthy (2003), Uremis et al. (2004), Haramoto and Gallandt (2004), Boydston and Al–Khatib (2006), Awan et al. (2012), Lawley et al. (2012), Syed et al. (2014), Mohamed and El–gawad (2014), Lemerle et al. (2017), Marinov–Serafimov et al. (2019); Poaceae (1GRAF) family species in the studies of Einhellig et al. (1982), Awan et al. (2012), de Bertoldi et al. (2012), Anwar et al. (2013), Fragasso et al. (2013), Golubinova and Ilieva (2014); Apiaceae (1UMBF) family species in the studies of Yurchak (2005), Syed et al. (2014), Singh et al. (2016); Asteraceae (1COMF) family species in the studies of Izzet et al. (2004), Awan et al. (2012), Możdżeń et al. (2018), Marinov–Serafimov et al. (2019); Amaranthaceae (1AMAF) family species in the studies of Shahrokhi et al. (2011), Iqbal and Fry (2012), Bakhshayeshan-Agdam et al. (2015), Gfeller et al. (2018), Prinsloo and Plooy (2018), Carvalho et al. (2019), VanVolkenburg et al. (2020); Polygonaceae (1POLF) family species in the studies of Anwar et al. (2013). According to the research results of the above–mentioned authors, the highest level of allelopathic potential was noted for the Asteraceae and Poaceae family representatives, and among the parasitic representatives of the Convolvulaceae family, in particular the Cuscuta (1CVCG) genus. Unlike other crops, which were studied in the above publications, oilseed radish has a high level of tolerance both in the assessment of the formation of laboratory germination capacity, and from the position of initial growth processes, although the nature of allelopathic impact on the basic indicators in relation to other crops has certain similarities.

The data obtained also allow us to determine the most harmful type of contamination for oilseed radish agrophytocoenosises, which is based on estimates of the level of competitive and allelopathic pressure, given the previously studied vitality tactics of a variety of weed species in the oilseed radish cenosises of different technological density (Tsytsiura, 2020), as well as estimates made in other studies (Smith, 2013; Zimdahl, 2004, 2018) on the formation of competitive relationships and the degree of dominance of weed agrophytocoenosises. In this regard, for oilseed radish in view of the OAP of the studied species, the total harmfulness of the types of infestation will increase in the following order: young – rhizomatous – young–rhizomatous, soboliferous, young–soboliferous – rhizomatous–soboliferous – young–soboliferous–rhizomatous. At the same time, the maximum allelopathic pressure will be noted by analogy with the coenotic pressure in cenosis (Zimdahl, 2004, 2018) provided that participation in the formation of stem and cenosis tiers of one–third of species with OAP from 0.5.

Thus, oilseed radish has a sensitive reaction to water extracts from 77 species of weeds in the range of concentrations from 0.25% to 16% (w v^{-1}) with a boundary value of formation of the minimum level of laboratory seed germination at a concentration of 4.0%. It was found that the soil substrate alleviates the allelopathic impact of water extracts from weeds plants with a decrease in the OAP value by one or two steps of the classification gradation of the indicator in the 0.26–0.75 interval.

Based on the OAP indicator in relation to the formation of laboratory germination of seeds, 10 groups were formed from 0.26 to 0.75 with 0.04 step. In the OAP 0.5–0.75 interval, which corresponds to the impact of species with high allelopathic potential, 35 species out of 77 studied were included. Depending on the determined OAP indicator (in the interval ratio between water and soil germination substrates) and given the prevalence of the main weed species in the oilseed radish agrophytocoenosises in terms of allelopathic potential with respect to the formation of the level of laboratory germination, it can be placed in the following orde: *Setaria glauca* L. (OAP 0.35–0.41) – *Polygonum lapathifolium* (L.) Delarbre (0.45–0.54), *Setaria viridis* (L.) Palisot de Beauvois (0.48–0.52) – *Ambrosia artemisiifolia* L. (0.47–0.53) – *Sonchus arvensis* L. (0.52–0.56) – *Echinochloa crus-galli* (L.) P.Beauv. (0.47–0.57) – *Agropyron repens* (L.) Gould (0.56–0.60) – *Polygonum convolvulus* (L.) Löve (0.58–0.60) – *Equisetum arvense* L. (0.59–0.60) – *Convolvulus arvensis* L. (0.57–0.61) – *Galinsoga parviflora* Cavanilles (0.57–0.62) – *Cirsium arvense* (L.) Scopoli (0.54–0.63) – *Chenopodium album* L. (0.63–0.67) – *Amaranthus retroflexus* L. (0.64–0.67) – *Acroptilon repens* (L.) de Candolle (0.65–0.66) – *Cuscuta campestris* Yuncker (0.68).

There are 8 classification groups from 0.30 to 0.70 with an interval step of 0.04 according to the OAP indicator in relation to the initial growth processes of oilseed radish plants. 33 plant species out of 77 analyzed (42.9%) are classified among those with OAP value of 0.50 and higher. By the size of the total allelopathic potential and given again the prevalence of certain species in the oilseed radish agrophytocoenosis, the main harmful weed species can be placed in the following order: *Sonchus arvensis* L. (integral OAP 0.31) – *Setaria glauca* L. (0.38) – *Polygonum lapathifolium* (L.) Delarbre (0.43) – *Chenopodium album* L. (0.43) – *Ambrosia artemisiifolia* L. (0.45) – *Convolvulus arvensis* L. (0.46) – *Agropyron repens* (L.) Gould (0.48) – *Carduus acanthoides* L. (0.51) – *Echinochloa crus–galli* (L.) P.Beauv. (0.51) – *Equisetum arvense* L. (0.51) – *Galinsoga parviflora* Cavanilles (0.52) – *Cirsium arvense* (L.) Scopoli (0.54) – *Polygonum convolvulus* (L.) Löve *(0.55) – Amaranthus retroflexus* L. (0.55) – *Lactuca serriola* L. (0.57) – *Cynodon dactylon* (L.) Pers. (0.58) – *Lepidium draba* L. (0.63) – *Cuscuta campestris* Yuncker (0.64) – *Acroptilon repens* (L.) de Candolle (0.66).

Considering the obtained allelopathic potential rows, the maximum harmfulness of weed cenosis in the oilseed radish agrophytocoenosises will be noted if at least one third of representatives of the specified allelopathic row are combined during the vegetation of the crop with the maximum allelopathic effect of influence in case of young–soboliferous-rhizomatous type of infestation.

4.3. Effectiveness of weed control using oilseed radish

Plant mulch of cruciferous siderates covers the soil from the sun's rays, which are activators of the process of germination of certain groups of weeds, and exerts allelopathic inhibition on the germination of annual weeds (Brust et al., 2014; Didon et al., 2014), which reduces the need to use herbicides. By wrapping the siderate phytomass, cultivated plants increase their phytomass faster, which increases their competitiveness against weeds, due to the improvement of the agrochemical, agrophysical, and microbiological condition of typical black soil.

The research was carried out in a short-rotation crop rotation: peas – winter wheat – sugar beets – barley. The sugar beet fertilization scheme included:

– Control (wrapping only post-harvest remains of winter wheat).

– Post-harvest siderate of oilseed radish.

– Post-harvest siderate of phacelia.
– Post-harvest siderate of buckwheat.
– Wrapping 25 t/ha of manure.
– Wrapping of mineral fertilizer $N_{125}P_{63}K_{150}$.

Before sowing siderates, surface peeling was carried out for 4–6 cm. After plowing with green manure, in the following years 2001–2006, sugar beets (Umansky ChS-97 hybrid) were grown according to the technologies recommended for the location of the experiment

Among the post-harvest sowings of siderates, compared to the control without siderate, the lowest number of weeds was found for oil radish – 4.8 pcs. m^{-2} and their weight – 28.1 g m^{-2}, which differed by 73 and 81% from the control without siderate, where the total number of weeds was determined at the level of 17.8 pcs. m^{-2}, and biomass – 150 g m^{-2} (Table 4.14). A smaller decrease in the number of weeds was established for the pygmy-leaved facies.weight – by 64%, and weight – by 51%, compared to the control, and the lowest – for seed buckwheat – 39 and 51%, respectively.

Sowing of green fertilizers most noticeably reduced, compared to the control (without siderate), weediness by annual summer weeds, which, compared to wintering and perennial weeds, were the most common. Thus, in siderat crops, the number of early spring weeds decreased by 3.8–6.4 pcs. m^{-2}, and late spring weeds – by 1.6–3.8 pcs. m^{-2}. Their mass differed from the control without siderate – by 35.4-52.4 g m^{-2} and 15.4–23.2 g m^{-2}, respectively. A significant reduction in weight weediness due to wintering weeds – by 15.4–23.2 g m^{-2} and perennial weeds – by 3.2–5.8 g m^{-2}, and quantitative – only by perennial weeds – by 0, 8–1.4 pcs. m^{-2}.

Siderate of oil radish most suppressed seedlings and subsequent growth and development of weeds due to the densest cover of green mass. It was here that the strongest feedback was established between the above-ground mass of siderate and the number of weeds – r = -0.55 and their mass – r = -0.56.

Under a less powerful cover of the post-harvest sowing of siderate of Phacelia pygmylum, the correlation between the above-ground mass of siderate r = –0.53 and the number and mass of weeds – r = –0.51 was weaker.

The stem of the post-harvest buckwheat siderate was the least dense at the time of plowing, as this heat-loving culture stopped vegetation under the influence of low temperatures, which caused the highest weediness among the siderate crops. A correlation between the above-ground mass of buckwheat and its weediness was not established.Thus, during the cultivation of siderats, the post-harvest sowing of oil radish was the least weedy, and the sowing of buckwheat was the most weedy. After the overwintering of plowed organic and mineral fertilizers compared to the control without them, differences in the distribution of weed seeds in the soil were determined (Table 4.14).

At the beginning of the growing season, the number of all weed seeds in the 0–30 cm soil layer on the background of green fertilizers was significantly lower – by 5.4–13.1 million seeds ha^{-1} or 4.7–11.5%, compared with control without siderate, where it is set at the level of 114.3 million units ha^{-1}.

Table 4.14

Number and mass of weeds before plowing post-harvest siderates, average for 2000–2004 (Mishchenko and Zakharchenko, 2019)

Variant	Number of weeds, pcs. m^{-2}					Mass of weeds, g m^{-2}				
	biological groups of weeds				In total	biological groups of weeds				In total
	spring early	spring late	wintering	perennial		spring early	spring late	wintering	perennial	
Without siderate (control)	9.0	5.6	1.6	1.6	17.8	65.2	53.0	25.4	6.2	150
Post-harvest siderate of oilseed radish	2.6	1.8	0.2	0.2	4.8	12.8	12.7	2.2	0.4	28.1
Post-harvest siderate of Phacelia tansy	3.6	2.2	0.2	0.4	6.4	21.8	15.0	2.4	1.6	40.8
Post-harvest siderate of sowing buckwheat	5.2	4.0	0.8	0.8	10.8	29.8	30.6	10.0	3.0	73.4
LSD_{05}	1.7	1.3	3.4	0.7	3.4	11.1	12.0	9.1	2.7	26.5

Plowing with 25 t ha^{-1} of manure increased the potential clogging of the 0-30 cm soil layer at the beginning of the growing season by 29 million units ha^{-1} or 25%; for the application of mineral fertilizers, it was at the control level – 114.6 million pcs. ha^{-1}.

The distribution of weed seeds by siderates contributed to the reduction of the potential clogging of the upper soil layer. Thus, for oil radish, the lowest share of seed stocks was found in the 0–5 cm layer – 14% and 5–10 cm – 14.8%, and the highest – after plowing with 25 t ha^{-1} of manure and mineral fertilizers $N_{125}P_{63}K_{150}$ – 16.4 and 16 %.

The reduction of potential weediness against the background of green fertilizers is explained by the effect of two factors: 1) pre-sowing soil cultivation and subsequent rolling of the soil under intermediate crops of siderates stimulated the germination of weed seeds; 2) plowing of plant biomass activated the activity of soil biota, which ensured intensive destruction of organic matter and weed seeds. This explains that with the plowing of the largest amount of radish siderate phytomass, the most significant difference in the number of weed seeds of the upper layers of the soil 0–5 cm – by 3.4 million units/ha and 5–10 cm – by 4.6 million. units/ha to the control without siderate, where weed seed reserves were 18.8 million units/ha in the 0–5 cm layer, and 18.2 million units ha^{-1} in the 5–10 cm layer. Plowing of oil radish also provided the most significant reduction of weed seed reserves in the 10–20 cm soil layer – by 2.1 million pieces/ha and in the 20–30 cm layer – by 3.0 million pieces/ha, compared with the control without siderate, where their number was 38.8 and 38.5 million pcs. ha^{-1}.

In the siderate of the pygmy leaf phacelium, the potential clogging at the time of vegetation recovery was significantly higher, compared to oil radish, in the soil layer of 0–5 cm – by 0.8 million units/ha, 5–10 cm – by 0.7 million . pcs. ha^{-1}, and in the arable (0¬30 cm) layer – by 3.0 million pcs./ha, and compared to the control – it decreased noticeably – in the range of 1.4–10.2 million pcs. ha^{-1}. Against the background of post-seeded buckwheat siderate, the highest potential clogging of the soil layer 0–30 cm was established – 108.9 million pcs. ha^{-1} among green fertilizers, but it significantly decreased, compared to the control without siderate, in the soil layer – 0–5 cm – by 2.5 million pieces/ha, 5–10 cm – by 1.7 million pcs. ha^{-1}, and in the arable (0–30 cm) layer – by 5.0 million pcs. ha^{-1}.

Among the post-harvest siderates, the phytomass of oil radish had the most significant effect on reducing the potential clogging of the soil layer 0–30 cm – r = 0.9. The correlation coefficient was slightly lower for the siderate of the phacelium pygmy – 0.87, and the smallest for the siderate of the buckwheat – r = 0.77.

The phytomass of oil radish siderate had the greatest positive effect on reducing the number of weed seeds in the soil layers – 70.0–92.5%, the phytomass of phacelia had a lesser effect – 63.0–87.3%, and the least buckwheat – 51.0–63.2% (Table 4.15).

Table 4.15

Potential soil clogging at the beginning of the growing season under different fertilization backgrounds, average for 2001–2005, million units ha^{-1} (Mishchenko and Zakharchenko, 2019)

Variant	Soil layer, cm								
	0–5		5–10		10–20		20–30		0–30
	million units ha^{-1}	% to total	million units ha^{-1}	% to total	million units ha^{-1}	% to total	million units ha^{-1}	% to total	In total, million units ha^{-1}
Without siderate (control)	18.8	16.4	18.2	15.9	38.8	33.9	38.5	33.7	114
Post-harvest siderate of oilseed radish	14.2	14.0	14.8	14.6	35.8	35.4	36.4	36.0	101
Post-harvest siderate of Phacelia tansy	15.0	14.4	15.5	14.9	36.5	35.1	37.1	35.6	104
Post-harvest siderate of sowing buckwheat	16.3	15.0	16.5	15.2	37.9	34.8	38.2	35.1	109
25 t ha^{-1} manure	23.5	16.4	22.9	16.0	48.6	33.9	48.4	33.8	143
Mineral fertilizers $N_{125}P_{63}K_{150}$	18.8	16.4	18.3	16.0	38.8	33.9	38.7	33.8	115
LSD_{05}	0.4		0.6		1.0		1.2		1.0

It was established (Mishchenko and Zakharchenko, 2019) that green fertilizers had a noticeable effect on the distribution of weed seeds in the 0–30 cm soil layer. If manure and mineral fertilizers were applied, weed seeds were distributed in the soil as well as in the control without siderate – the largest their share was 16.4% in the upper layers of the soil 0–5 cm and 16.0% in 5–10 cm, then with oil radish siderate, compared to the control without it, the share of seeds of potential litterers decreased in the upper soil layer by 0– 5 cm – by 2.4% and in the 5–10 cm layer – by 1.3%, for pygmy phacelia – by 2.0 and 1.0%, and for buckwheat – by 1.5 and 0.8% . The decrease in the number of weed seeds is due to the activation of the natural processes of destruction of soil organic matter and the lack of replenishment of the seed fund of polluters, established by the application of manure (Table 4.16).

Table 4.16

The share of influence of the type of siderate on the potential clogging of soil layers, % (Mishchenko and Zakharchenko, 2019)

Variant	Soil layer, cm				
	0–5	5–10	10–20	20–30	0–30
Post-harvest siderate of oilseed radish	70.0	72.5	81.3	92.5	81.3
Post-harvest siderate of Phacelia tansy	63.0	69.0	78.0	87.3	76.4
Post-harvest siderate of sowing buckwheat	51.0	55.7	59.5	63.2	59.8

Since the majority of weeds germinate from a layer of up to 10 cm, this distribution of them in the soil subsequently caused a lower actual weediness of sugar beet crops on the background of siderates, compared to the control without them. Thus, against the background of oil radish siderate, both the number of weeds – 19.2 pcs./m^2 and their mass – 354 g/m^2 was determined to be the lowest in sugar beet crops (Table 4.17).

Against this background, the most significant reduction in the number of weeds in sugar beet crops was established – by 39% and their weight – by 23%, compared to the control, where the number of weeds was 31.4 pcs. m^{-2}, and their weight was 460 g m^{-2}.

In comparison with the control without siderate, the number of weeds in sugar beet crops was significantly lower by 31% and their weight by 18%.

Buckwheat green fertilizer among siderates ensured a significantly higher number of weeds in sugar beet crops – 27.6 pcs. m^{-2} and their weight – 436 g m^{-2}. In general, weediness on the background of seeded buckwheat siderate was significantly lower, compared to the control without siderate, in terms of the number of weeds in sugar beet crops – by 12%.

Since the greatest potential clogging was determined in the upper 0–10 cm soil layer when 25 t ha^{-1} of manure was applied during vegetation recovery, the sugar beet crops had the highest number of weeds –

40.0 pcs./m^2 and their mass – 731 g m^{-2}, which significantly exceeded both the control and green manure backgrounds. With the introduction of mineral fertilizer $N_{125}P_{63}K_{150}$ under sugar beets, there was no significant increase in the number of weeds compared to the control without siderate, however, their weight in sugar beet crops increased significantly by 141 g to 601 g m^{-2}.

Table 4.17

Distribution of biological groups of weeds in sugar beet crops under different fertilization backgrounds, average for 2001–2005 (Mishchenko and Zakharchenko, 2019)

Variant	Biological group of weeds												In total	
	spring early			spring late			wintering			perennial				
	million units ha^{-1}	% to total	g m^{-2}	million units ha^{-1}	% to total	g m^{-2}	million units ha^{-1}	% to total	g m^{-2}	million units ha^{-1}	% to total	g m^{-2}	ps. m^{-2}	g m^{-2}
Without siderate (control)	15.9	50.7	200	10.8	34.4	177	2.1	6.6	43.9	2.6	8.3	40.0	31.4	460
Post-harvest siderate of oilseed radish	9.9	51.4	165	7.9	41.0	155	0.7	3.8	19.1	0.7	3.8	15.7	19.2	354
Post-harvest siderate of Phacelia tansy	11.1	50.9	174	8.9	41.1	162	0.9	4	22.3	0.9	4.0	17.8	21.8	376
Post-harvest siderate of sowing buckwheat	14.1	51.1	203	10.3	37.3	173	1.5	5.5	34.1	1.7	6.0	26.3	27.6	436
25 t ha^{-1} manure	19.3	48.2	308	15.1	37.8	308	2.9	7.2	67.1	2.7	6.8	48.8	40.0	731
Mineral fertilizers $N_{125}P_{63}K_{150}$	15.7	48.0	241	12.5	38.2	263	1.9	5.9	49.1	2.6	8.0	47.9	32.7	601
LSD_{05}	1.7		23.4	1.7		35.2	0.8		18.0	0.6		10.2	3.3	52.6

Fertilization backgrounds had almost no effect on the species composition of sugar beet weeds, their crops were characterized by the early-year weed type – from 91 to 96% of early-year weed: common sedge (*Amaranthus retroflexus* L.), flat common (*Echinochloa crusgalli* L.), mouse green, (*Setaria viridis* L.), white quinoa (*Chenopodium album* L.), field sedge (*Thlaspi arvense* L.), Canadian sedge (*Erigeron canadensis* LJ; among perennial weed species, weakly developed yellow thistles (*Sonchus arvensis* L.) and field birch (*Convolvulus arvensis* L.).

In the structure of weediness of sugar beet crops grown on the background of siderate of oil radish or Phacelia pysmofolia, the share of wintering and perennial weeds decreased to 4%, while in the control without siderate it fluctuated within 8%. The most noticeable increase in the structure of weediness was the increase in the share of late spring weeds when grown on the background of siderate of oil radish and phacelia pysmolys of sugar beet – up to 41%, for their share in the control without siderate at the level of 34%.

Against the background of siderates, compared to the control without them, an increase in the share of monocotyledonous weeds from the biological group of early spring weeds was noted – within 1–2%, and a decrease in the share of dicotyledonous weeds. When manure was applied, compared to the control without siderate, on the contrary, the share of monocotyledonous weeds decreased by 1–3% and, accordingly, the share of dicotyledonous weeds increased.

Determination of the dynamics of weediness of sugar beet crops established its peak in the middle of the growing season. For plowing with 25 t/ha of manure, both the number of weeds at the time of closing the rows of sugar beets was the highest – 56 pcs. m^{-2}, and their weight – 1214 g m^{-2}, which prevailed over the control without siderate in terms of the number of weeds on 27%, and by their weight – by 62%.

In the crops of sugar beets against the background of siderate of oil radish and Phacelia pysmolystia, significantly less weediness was determined with a difference to the control in the range of 20–50%.

The highest rates of weediness in the middle of the growing season (in June and July) are due to sufficient heat and precipitation and the slow formation of phytomass in sugar beets in the first half of the growing season, which did not ensure phyto-coenotic suppression of weeds.At the time of the emergence of sugar beet seedlings, the smallest number of weeds was determined for the siderate of oil radish – 14.2 pcs. m^{-2} and their weight – 41.7 g m^{-2}. This is due to the mechanical loosening of the inter-rows in the sugar beet crops and the inhibition of weed seed germination under the action of the decomposition products of the phytomass of the green fertilizer.

Setting the minimum mass of weeds at the time of emergence from 41.7 to 108 g m^{-2} is due to the shortest period of their vegetation and the low weight of representatives of each species.

At the time of harvesting of sugar beets, weed plants in crops reached the largest mass, because their vegetation was the longest, however, due to the lowest density of weeds, their mass was lower than during the recording in the middle of the vegetation and ranged from 439 to 821 g m^{-2}.

The least weedy crops of sugar beets were under the green manure of oil radish, which differed significantly from the background of seeded buckwheat siderate, control without siderate and plowing of traditional fertilizers. The high efficiency of oil radish siderate in terms of reducing actual weediness is due to the presence in cruciferous plants of a herbistatic effect from the decomposition products of plowed phytomass. This confirms the established inverse closest correlation between the mass of oil radish siderate and the number of weeds – $r = -0.82$ and their mass – $r = -0.89$, and the highest share of the influence of the phytomass of green fertilizer on weediness indicators – respectively 67 and 80%.

The proportion of the influence of phytomass on the number of weeds was 59% and 72% for the siderate of *Phacelia pygmaeus*, and the lowest for the siderate of buckwheat was 48 and 62%, respectively. Due to the improvement of the nutrition background, the weight of one weed plant increased with the application of fertilizers: on the background of the siderate of oil radish for the cultivation of sugar beets – by 3.8 g, the application of manure – by 3.6 g, and mineral fertilizers – by 3.7 g.

At the time of harvesting sugar beets, the largest decrease was found, compared to the count at the beginning of their cultivation, in the number of weed seeds in the 0–30 cm soil layer when using oil radish siderate – by 2.5 to 98.5 million pieces ha^{-1}).

The reduction of weed seed stocks occurred due to its destruction in the soil, germination and avoidance of ripening of weeds, the seedlings of which were destroyed in sugar beet crops by mechanical processing.

Thus, the lowest potential weediness of the 0–30 cm soil layer was established on the background of the siderate of oil radish during the cultivation of sugar beets – 98.5 million units ha^{-1}, which differed significantly from the rest of the fertilization backgrounds, and decreased most noticeably – by 12%, compared to the control without siderate, where the number of weeds was 112.3 million units ha^{-1}.

The number of weed seeds in the 0-30 cm soil layer was significantly reduced by 9% compared to the control without siderate before harvesting sugar beets, and by 5% with buckwheat siderate.

Application of 25 t ha^{-1} of manure provided the largest number of weed seeds in the 0-30 cm soil layer before harvesting sugar beets – 140.7 million pieces ha^{-1}, which exceeded the control without siderate by 25%. Plowing of mineral fertilizer $N_{125}P_{63}K_{150}$ formed potential clogging at the level of control without siderate – 112.5 million units ha^{-1}. (Table 4.18).

In the surface (0–10 cm) layer of the soil, a smaller number of weed seeds was determined on the background of green manure in the range of 12–24%, compared to the control without it. The lowest number of weeds was determined for the siderate of oil radish in the upper layer of 0–5 and 5–10 cm under the sugar beet crops – 13.6 and 14.2 million units/ha, which provided the smallest share of the number of weeds in these soil layers Yanivs – between 13.8 and 14.4%.

Under siderates of the phacelia of pygmaeus and buckwheat, the share of seeds in the upper layers increased to 14–15%, and in the control and against the background of plowing with 25 t/ha of manure or mineral fertilizer $N_{125}P_{63}K_{150}$, it fluctuated within the range of 15.8–16.4%. Such dynamics of seed distribution in the surface (0–10 cm) layer indicates the appearance of possible weed seedlings in smaller quantities against the background of green fertilizers.

The closest inverse correlation was established between the phytomass of the post-harvest siderate and the potential clogging of the arable (0–30 cm) soil layer at the time of harvesting sugar beets after oil radish r = –0.9, and the lowest – when using buckwheat siderate – r = -0 ,77.

Between the phytomass of the post-harvest siderate of Phacelia and the potential clogging of the soil, the correlation was determined at the level of 0.87, which indicates a lower anti-weed efficiency than that of oil radish.

Table 4.18

Potential soil clogging before harvesting sugar beets under different fertilization backgrounds, average for 2001–2005, million units ha^{-1} (Mishchenko and Zakharchenko, 2019)

Variant	Шар грунту, см								
	0–5		5–10		10–20		20–30		0–30
	million units ha^{-1}	% to total	million units ha^{-1}	% to total	million units ha^{-1}	% to total	million units ha^{-1}	% to total	In total, million units ha^{-1}
Without siderate (control)	18.3	16.3	17.7	15.8	38.1	33.9	38.2	34.0	112.3
Post-harvest siderate of oilseed radish	13.6	13.8	14.2	14.4	34.9	35.4	35.8	36.3	98.5
Post-harvest siderate of Phacelia tansy	14.5	14.3	14.9	14.7	35.7	35.1	36.6	36.0	101.7
Post-harvest siderate of sowing buckwheat	15.8	14.8	16.0	15.0	37.1	34.8	37.7	35.4	106.6
25 t ha^{-1} manure	22.8	16.2	22.2	15.8	47.6	33.8	48.1	34.2	140.7
Mineral fertilizers $N_{125}P_{63}K_{150}$	18.5	16.4	17.8	15.8	38.0	33.8	38.2	34.0	112.5
LSD_{05}	0.5		0.7		1.0		1.2		1.0

In the studies of Perchuk (2008), the cultivation of the green mass of oil radish by shelf cultivation contributed to the reduction of the number of weeds and their mass in the sowing of corn for grain by 40–60% (Table 4.19).

In continuation of the above, Babych et al.(2011) emphasizes that in order to increase the anti-weed and anti-nematode effectiveness of crop rotations, it is necessary to saturate them with cabbage crops as much as possible.

At the same time, it is recommended to increase the sowing rate by 20–25% to the recommended one. Their research established that the thickened crops of intermediate cabbage crops reduced the total weediness with small and perennial weeds, including creeping wheatgrass, by up to 60%. Two-time cultivation of oil radish reduced the number of growing weeds by 72–85% (Table 4.18). Based on the presented results, the authors concluded that the cultivation of cruciferous crops in intermediate crops should be considered not only as a factor in strengthening the forage base of farms, but also as a technique that has a positive effect on the phytosanitary situation in crop rotation. This is especially important for the mobilization of natural resources that determine the high productivity of agrophytocenosis.

Table 4.19

The influence of sideration and main tillage on the weediness of corn crops, pcs. m^{-2} (Perchuk, 2008)

Variant	Number of weeds, pcs. m^{-2}	Efficiency, %		Mass of weeds, kg m^{-2}	Efficiency, %	
		from processing	from siderates		from processing	from the side-ration
Plow on 25–27 cm						
Root and stubble remains of winter wheat (control)	165	0	-18	3,6	0	-13
Manure – 40 t ha^{-1}	201	+22	0	4,1	+15	0
Oilseed radish	82	-50	-59	1,6	-54	-61
Oats + peas	138	-8	-31	3,1	-14	-25
Straw – 4 t ha^{-1}	178	+8	-11	3,4	-6	-18
Chisel on 25–27 cm						
Root and stubble remains of winter wheat (control)	225	0	-10	3,7	0	-15
Manure – 40 t ha^{-1}	250	+11	0	4,4	0	0
Oilseed radish	98	-43	-61	2,1	-44	-52
Oats + peas	200	-9	-20	3,1	-17	-29
Straw – 4 t ha^{-1}	236	+5	-6	3,3	-11	-24
Flat-cut on 25–27 cm						
Root and stubble remains of winter wheat (control)	200	0	-13	4,0	0	-8
Manure – 40 t ha^{-1}	230	+15	0	4,3	+8	0
Oilseed radish	90	-45	-61	2,6	-35	-40
Oats + peas	182	-9	-21	3,5	-12	-18
Straw – 4 t ha^{-1}	195	-1	-15	3,5	-11	-18
LSD_{05}	51			0,7		

We came to the same conclusions in our research on the herboregulatory effectiveness of oil radish in the system of biological control of weediness (Table 4.20–4.21, Figures 4.13–4.15).

The presented data prove that oil radish as a precursor provides 1.6–1.7 times higher levels of phytosanitary purity of crops compared to the most recommended predecessors – soybeans and peas. This, in turn, emphasizes the importance of horseradish for herbicide-free weed control.

The analysis of the effectiveness of the use of cruciferous crops, including oil radish, in the control of the number of weeds was made in the studies of Lawley et al. (2012). Both winter annual and summer annual weed species were selected for the bioassay as the type and duration of forage radish weed suppression was unknown at the time. We hypothesized that decomposing forage radish residues would reduce the spring emergence of planted weed seeds relative to a no cover crop treatment if allelopathy was the dominant mechanism ofweed suppression. Weed and lettuce emergence was not suppressed by forage radish relative to the no cover crop control or the oat cover crop treatment regardless of weed type (summer vs. winter annual) or species (Figure 4.16). Weed emergence was higher in the forage radish treatment for several of the weeds species planted, including common chickweed, common lambsquarters, redroot pigweed, and common ragweed. Emergence of lettuce occurred much earlier (February) in forage radish treatments than the other two treatments (April) (Figure 4.16).

Stimulation of lettuce and weed seed emergence may have been due to higher soil nitrate levels in the forage radish treatment (Figure 4.16). Some weed species, such as common lambs-quarters, use nutrients as a signal to promote germination.

Table 4.20

The influence of oil brassicacea crops on weediness by cereal weeds (on average over 5 years) (Babych et al., 2011)

Variant	Number of grass weeds before harvesting*, pieces m^{-2}		
	I	II	III
Control – winter wheat without sowing intermediate crops	37.6	51.3	62.4
Winter wheat + oilseed radish g/f	38.1	21.8	–
Winter wheat + spring rapeseed g/f	38.4	23.9	–
Winter wheat + mustard g/f	36.9	27.8	–
Oilseed radish + oilseed radish g/f	23.7	14.3	–
Winter wheat + oilseed radish g/f + oilseed radish g/fz	37.2	20.6	12.7
Winter rye + oilsed radish g/f + oilseed radish g/fz	32.5	17.1	9.6

* I, II, III – harvesting of the main and intermediate crops, respectively;
g/f, g/fz – green fodder and green fertilizer.

Table 4.21

Total littering of crops of winter wheat varieties depending on the predecessor (average for 2010–2012) (Tsytsiura, 2014)

Predecessor	Myronivska 67		Donetska 48	
	g m^{-2}	in total phytomass, %	g m^{-2}	in total phytomass, %
Oilseed radish for green fodder (sowing rate of 3.0 million pieces ha^{-1} of similar seeds, row sowing)	51.4 ± 2.9	10.4	53.6 ± 3.2	9.6
Oily radish for seeds (sowing rate of 1.5 million pcs. ha^{-1} of similar seeds, inter-row sowing)	62.3 ± 2.3	12.4	68.6 ± 3.3	11.3
Corn for green fodder	106.8 ±3.4	29.2	112.4 ± 2.7	31.3
Soybean	81.9 ± 2.7	13.2	79.4 ± 2.1	12.7
Winter rape	96.3 ± 1.8	25.1	94.2 ± 3.3	23.8
Pea	91.7 ± 3.6	17.2	89.3 ± 2.4	16.4
LSD $_{05}$	3.2	–	3.7	–

Figure 4.13 – Active inhibition of weed development in oil radish crops due to high growth rates and intensive development of the assimilation surface (the upper position – in the phase of the beginning of flowering, the lower position – during the period of active fruiting, when due to the reduction or complete attenuation of growth processes and intensive reduction of foliage, weeds intensify their growth) (Tsytsiura, 2015)

Figure 4.14 – Ecological niche (lower tier) of weeds in oil-stemmed radish of the Zhuravka variety at the sowing rate of 2.0 million pieces/ha of similar seeds (Tsytsiura, 2015)

Figure 4.15 – Single plants of oil radish on an intensively weeded area on the experimental field of VNAU, 2014 (the number of weeds is more than 450 plants/m2, due to the active growth rates, the plants compete effectively and continue to vegetate, entering the reproductive phase of development) (Tsytsiura, 2015)

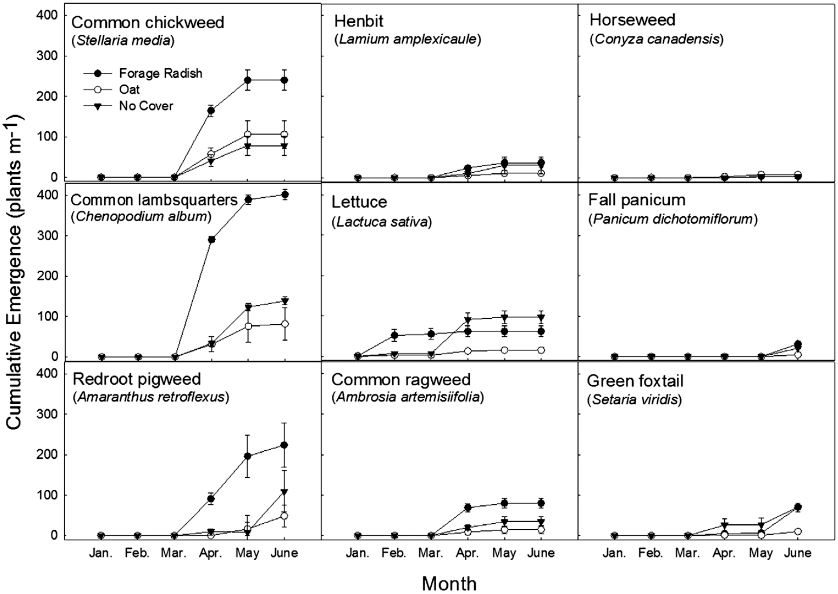


Figure 4.16 – Mean cumulative weed emergence of planted weed seeds and lettuce seeds below decomposing forage radish cover crop, decomposing oat cover crop, and no cover crop control treatments in 2006 at the USDA Beltsville Agricultural Research Center North Farm. Data points are an average of four observations. Error bars represent standard error of the mean (Lawley et al., 2012)

The results of these field bioassays agree with these earlier observations in 2 out of 3 site-years (Figure 4.17). The stimulatory effect of forage radish cover crops on winter annual weed species observed in this field bioassay contrast with the results of other field experiments (Lawley et al., 2011). In field experiments, Lawley et al. (2011) observed that forage radish cover crops delayed emergence of winter annual weeds relative to no cover crop. One of the differences between these field experiments and the field bioassay was the timing of weed seed introduction and germination. In the field bioassay, winter annual weeds in both forage radish and no cover control plots were forced to germinate in the spring, whereas many would naturally germinate and establish during the fall, as occurred in the no cover crop plots in the field experiments. The winter introduction date in the field bioassay also meant that planted weeds in the forage radish treatment were influenced only by residue decomposition and not by the fall cover crop growth as occurred in the field experiments. This further supports the hypothesis that forage radish weed suppression is the result of fall cover crop weed suppressiondue to rapid canopy development, rather than allelopathy.

Author hypothesized that if forage radish was allelopathic, lettuce or tomato germination and seedling growth under controlled environment conditions would be reduced in soils sampled below decomposing forage radish residues relative to a no cover crop control. We also hypothesized that the allelo-pathic effects of forage radish cover crops would be greater in soils collected during the time of most active radish decomposition in January than in soils collected during March. However, we reject both hypotheses based on assay results. In all but one case the significant differences between no cover crop and forage radish treatments indicated a stimulatory effect of forage radish, rather than an inhibitory effect, causing improved lettuce seedling biomass or tomato seed germination (Figure 4.17).

Tomato seed germination was greater in forage radish treatments relative to the no cover crop control in January and March for soils sampled at BARC-SF. Lettuce seedling DM was greater in forage radish treatments than in the no cover crop control in both January and February. These stimulatory effects of forage radish on lettuce and tomato agree with the findings of Exp. 2 and provide evidence to reject allelopathy as the mechanism of forage radish weed suppression. The stimulation of tomato seed germination and lettuce seedling DM in forage radish treatments could be due to the higher nitrate content of the soil sampled from the forage radish treatment (Figure 4.17).

One potential limitation of this experimental approach is higher temperature and moisture in the test chambers than in the field which could have caused loss of volatile allelochemicals, such as many ITCs. Petersen et al. (2001) conducted soil bioassays to evaluate the allelopathic effect of turnip-rape (B. rapa (Rapifera Group)-*B. napus* L.) mulch and identified ITCs present in both the plant tissue and soil. The ITC concentration in their study was 2300 times lower in the soil than in plant tissues and their disappearance from the soil was enhanced by saturated soil conditions and high temperatures. Sampling of soil for the bioassay also resulted in the separation of soil and plant residues, the potential source for a continued supply of newly forming ITCs as these residues decomposed. However, if allelopathy was responsible for the strong weed suppression observed in the field, we would have expected to observe some suppressive activity in these soils, despite the potential attenuating conditions of this assay.

Author hypothesized that if allelopathy was the mechanism of forage radish weed suppression, then aqueous extracts of forage radish tissues would inhibit lettuce seed germination and root growth. Extracts of both forage radish shoot and root tissues were included in the experiment to differentiate the location of potential allelopathic compounds. The allelopathic potential of living forage radish plant tissues was compared to plant residues by preparing aqueous extracts of plant residues harvested in November before frost damage and decomposing plant residues harvested the following March. Oat was included as a treatment because it is another frost sensitive cover crop that is also reported to have allelopathic properties.

Aqueous extracts of living forage radish tissues harvested before frost in November had an inhibitory effect on lettuce germination and root length relative to a distilled water control treatment (Figure). Aqueous extracts of forage radish residues harvested in March had a stimulatory effect on relative lettuce root length and an inhibitory effect on relative lettuce germination only at the highest extract concentration. Plant tissue extracts had little effect on the relative shoot length of lettuce in both November and March (data not shown).

Despite differences in color and odor of the two extracts (forage radish root extracts had a very pungent odor and dark color), both shoot and root tissues of forage radish had similar effects on relative lettuce germination and relative root growth (Figure 4.18). Thus, no differential response was observed between forage radish roots and shoots. Aqueous extracts of living oat tissue harvested in November had similar effects on lettuce germination and root growth to those observed with forage radish shoot extracts (Figure 4.19). Extracts of oat residues harvested in March had no effect on relative lettuce germination. Extracts of oat residue harvested in March had the same stimulatory effect on lettuce roots length that was observed with forage radish residues.

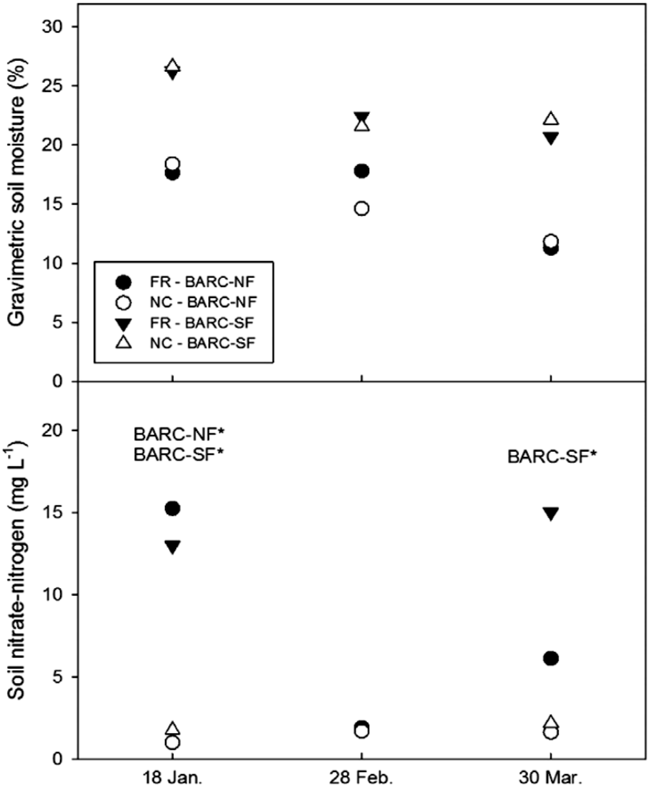


Figure 4.17 – Initial gravimetric soil moisture and soil nitrate-nitrogen content of soils sampled from forage radish (FR) and no cover crop (NC) treatments at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). Data points are an average of four observations. Significant differences between pairs of FR and NC treatments within a site are indicated by BARC-NF* or BARC-SF* (*P < 0.05*). No samples were available from the BARC-SF to measure soil nitrate-N for the 28 February sampling date (Lawley et al., 2012)

Relative lettuce seed germination and relative root length increased with the dilution of the full strength plant tissue extracts for all tissues sampled in November 2005 (Figure). The largest decline in relative germination occurred in forage radish root and shoot tissue extracts in proportions at or above 0.5 of the full strength extract. For extracts prepared from plant residues collected in March, lettuce germination declined only in full strength extracts prepared from forage radish root and shoot tissues. Extracts prepared from plant residue in March had a stimulatory effect on the relative root length of lettuce seedlings at extract proportions of 0.125 and 0.25 (Figure 4.20–4.21).

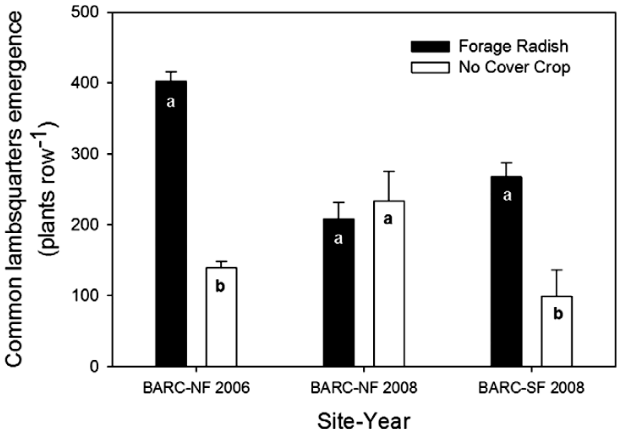


Figure 4.18 – Mean emergence of common lambsquarters below decomposing forage radish residues and a no cover crop control for 3 site-years at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). Bars represent an average of four observations. Bars topped with different letters indicate significant treatment differences at the p = 0.05 level within a site-year. Error bars represent stand error of the mean (Lawley et al., 2012)

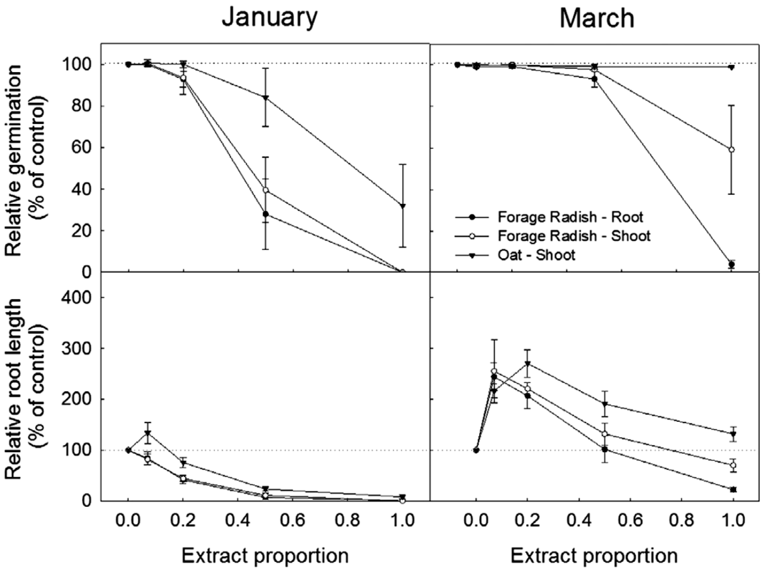


Figure 4.19 – Relative germination and root length of lettuce seedlings grown in aqueous plant tissue extracts. Germination and root lengths are expressed as a percent of the distilled water control. Extracts were prepared from fresh forage radish shoot, forage radish root, and oat shoot tissues collected on 7 Nov. 2005, and from plant residues collected on 24 Mar. 2006. Data points are an average of four observations. Error bars represent standard error of the mean

Although these results might suggest allelopathic potential, it is likely that the negative effects of full-strength forage radish and oat extracts on lettuce germination and root growth were due to the osmotic potential of the extract solutions. Regardless of whether the extract was prepared from plant tissue vs. residues or prepared from oat vs. forage radish, there was a general trend of decreasing lettuce seed germination and root length with increasing electrical conductivity, with a threshold between 2 and 4 dS m^{-1} (Figure 4.22). Both types of forage radish tissue extracts also had high electrical conductivity. The root tissue extract had a higher electrical conductivity and more inhibitory effect on lettuce seedlings than the shoot tissue extract.

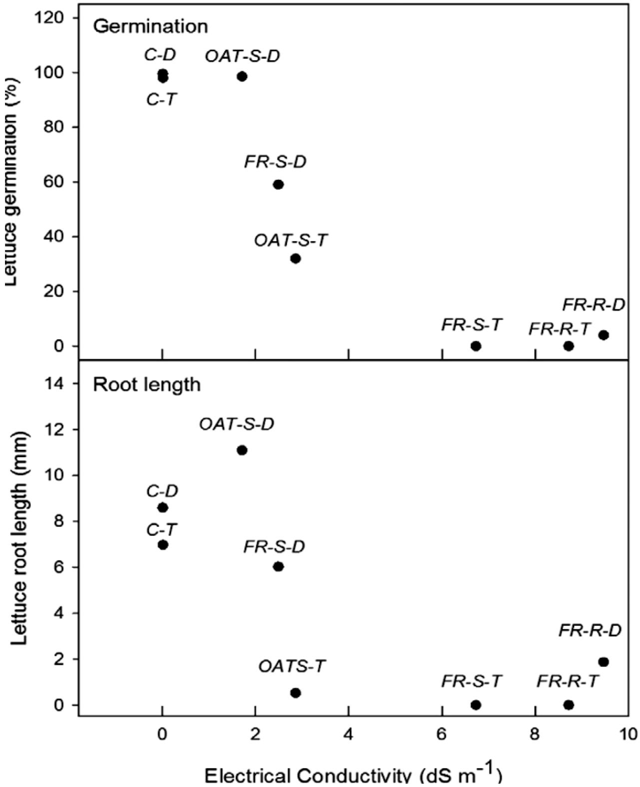


Figure 4.20 – Relationship between lettuce performance and electrical conductivity of aqueous plant tissue extracts and a distilled water control. Extracts were prepared from forage radish root (FR-R), forage radish shoot (FR-S), and oat shoot (OAT-S) and were compared to a distilled water control (C). Plant tissues (T) were harvested November 2005 and residues (D) harvested 24 Mar. 2006. Lettuce root length and germination are averages of four observations. Electrical conductivity was measured on one extract (Lawley et al., 2012)

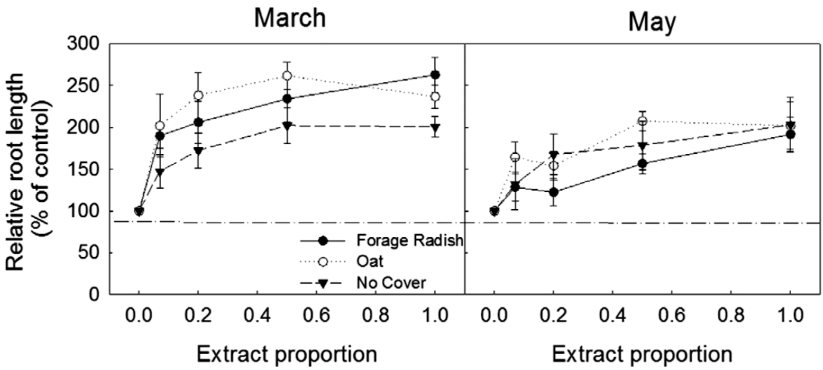


Figure 4.21 – Relative root length of lettuce seedlings grown in aqueous soil extracts. Root lengths are expressed as a percent of the distilled water control. Soil extracts were prepared from surface soil samples (0-5 cm) collected from forage radish, oat, and no cover crop field treatments on 28 Mar. and 30 May 2006. Data points are an average of four observations. Error bars represent stand error of the mean (Lawley et al., 2012)

Soil extracts were included in this experiment to test for potential retention of allelochemicals in the soil that could have a residual effect on weed seed germination and seedling growth. Because weeds naturally encounter allelochemicals within the soil environment, it was thought that soil extracts would provide a more realistic bioassay treatment than those prepared from plant tissues. We hypothesized that soil sampled beneath decomposing forage radish residues would decrease lettuce seed germination as well as root and shoot growth. We also hypothesized that these effects would be greater in March, when weed suppression was previously observed in the field by Lawley et al. (2011), than in May, when no weed suppression was observed.

Contrary to our hypotheses, the extracts prepared from cover crop-amended soil did not reduce lettuce seed germination or root growth. However, both cover crop treatment extracts as well as the no cover crop control extract had a stimulatory effect on lettuce root length relative to the distilled water control in March and May (Figure 4.22). Unlike extracts prepared from plant tissues, relative root length of lettuce seedlings increased with increasing soil extract proportion. The soil extracts had very low electrical conductivity (EC) (<0.1 dS m^{-1}). Soil extracts did not have an effect on relative shoot length or lettuce seed germination (data not shown). These results suggest that there were no or very low concentrations of allelochemicals present in the soil extracts and that noncover crop factors were the cause of lettuce stimulation, such as nutrients released by organic matter decomposition or from the soil cation exchange.

Results from the bioassay of plant tissue extracts can be explained by high EC levels, and thus only weakly suggest any potential for allelopathy. Certainly the results of the soil extract bioassay suggest that any inhibitory affect, whether due to allelopathy or osmotic potential, were not realized in the soil. Thus, aqueous extract bioassays did not present strong evidence in support of the allelopathy hypothesis for the occurrence of weed suppression following forage radish winter cover crop.

The author of the study draws the following conclusions: By employing multiple experimental approaches, the results of the four experiments in this study point to a common conclusion that early and competitive fall growth of forage radish is the dominant mechanism for weed suppression. Results of the forage radish residue-transfer experiment supported the hypothesis that fall cover crop weed competition due to rapid canopy development is the mechanisms of weed suppression following forage radish cover crops. The presence or absence of decomposing residue after winter-kill had relatively little effect on weed suppression. Field and controlled environment bioassays using cover crop-amended soil and aqueous extracts of cover crop tissues and amended soil did not reveal any allelopathic activity limiting seed germination or seedling establishment. In fact, forage radish-amended soils stimulated seedling growth in both types of bioassays.

Cover crop management strategies to maximize weed suppression following forage radish cover crops should ensure that crop rotations allow for early planting of forage radish cover crops. If factors such as late planting, drought, low soil fertility, or early frost limit the rapid canopy development of forage radish in the late summer or early fall, alternative pre-plant weed control is likely to be required the following spring. The results of this study along with the findings presented in Lawley et al. (2011) demonstrate that a competitive fall forage radish cover crop stand can achieved a relatively weed-free and residue-free seedbed in early spring to facilitate early crop planting operations. The seed bed following forage radish cover crops may be of special interest to organic farmers looking to eliminate or reduce spring tillage for direct seeding of subsequent vegetable or grain crops.

The use of oilseed radish to reduce weed infestation of potato agrocenoses proved to be effective (Mishchenko et al.m, 2019). The rate of early spring weeds increased and the winter annual weeds significantly decreased after green manure intercorporation-spring early weeds by number and weight (respectively, by 15 and 22%) and decreased wintering and perennial (11.5 and 22.0 and 2.0 and 2.3% respectively) (Figure 4.22). Compared with the control, under the cover of oil radish, the number of early weeds decreased by 4.2 plants m^2, and by weight-wintering-by 40 gm^{-2}, and the smallest number and weight of perennial weeds, respectively 2.4 plants m^{-2} and 13.4 gm^{-2}.

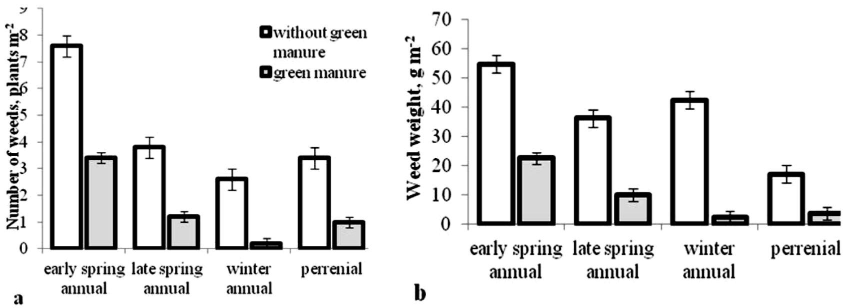


Figure 4.22 – Amount and weight of weeds before the primary soil tillage (x ± SE, n=10). *difference between variant without the incorporation of green manure iand with is statistically reliable P<0.05 (Mishchenko et al.m, 2019)

At the time of the growth recovery of weeds in the soil layer 0–30 cm deep after ploughing, we observed a proportional distribution of weed seeds within 30–40 % (Table 4.22). It has to say that potential infestation is the number of viable seeds in the soil and actual weed infestation is the number of weeds or their weight per unit area.

Table 4.22

Potential weed infestation of soil after green manure incorporation and tillage (April 2006–2010), mln pcs.ha^{-1} (Mishchenko et al.m, 2019)

Treatment		Soil layer, cm				Total
Green manure	Tillage system	0–5	5–10	10–15	20–30	0–30
without green manure	control (moldboard ploughing 28–30 cm)	20.8 ± 0.41	19.4 ± 0.28	36.7 ± 0.44	30.7 ± 0.24	107.6
	sweep ploughing 28–30 cm	24.5 ± 0.64*	35.1 ± 0.40*	25.7 ± 0.52*	21.9 ± 0.29*	107.2
	disking 13–15 cm	25.5 ± 0.33*	36.2 ± 0.36*	24.0 ± 0.34*	21.6 ± 0.18*	107.3
	disking 6–8 cm	28.1± 0.42*	35.0± 0.31*	22.6± 0.47*	21.5± 0.45*	107.2
green manure-incorporation	control (moldboard ploughing 28–30 cm)	19.9 ± 0.25	18.8 ± 0.22	36.0 ± 0.40	30.1 ± 0.38	104.8
	sweep ploughing 28–30 cm	23.5± 0.40*	33.5± 0.26*	25.4± 0.33*	21.7± 0.46*	104.1
	discing 13–15 cm	24.5± 0.32*	35.3± 0.21*	23.1± 0.75*	21.4± 0.32*	104.3
	discing 6–8 cm	26.8± 0.24*	33.4± 0.30*	22.4± 0.62*	21.2± 0.14*	103.8

*difference between variant without green manure and with is statistically reliable $p<0.05$

Oilseed radish green manure application on all types of soil tillage reduced the potential weed infestationat a depth of 20 cm to 0.2–1.6 mln. pcs.ha^{-1}. In the soil layer 20–30 cm deep, the potential weed infestation decreased by 0,6 million plants ha^{-1} only when using the method of green manure incorporation and conventional ploughing. Weed infestation was reduced by 2.8–3.4 mln.pcs.ha^{-1} in the soil layer 0-30 cm deep because of the use of green manure.

The actual weed infestation during the potato growing period determined the potential weed infestation in the upper layers of the soil. The smallest amount of weed seeds in the upper layer was set in the plots with green manure, and the smallest amount and weight of weeds in the field was observed – 10.6–20.8 plants m^{-2} and 132.4–728.0 gm^{-2} (Figure 4.23).

Based on data from the weed infestation, the result most similar to moldboard ploughing of 28–30 cm deep was sweep ploughing. The difference between these two methods in weed weight at the time of the seedlings emergence (1.3 gm^2) was not significant under the green manure application. During the potato growing period using discing at a depth of 13–15 cm, the amount and the weight of weeds, compared with mouldboard ploughing and sweep ploughing methods on both nutrients backgrounds, substantially increased by 5.0–20.8 plants m^{-2} and 33.0–346.8 gm^{-2}, respectively. The largest actual weed infestation was seen when discing at 6-8 cm; in comparison with other variants, the amount and weight of weeds increased significantly to 23.8–77.8 plants m^{-2} and 209.9–1089.8 gm^{-2}.

The smallest quantity of weeds were observed at the time of the potato harvest-10.6–36.2 plants m^{-2}, because it was the end of growing period. The smallest amount of weeds was observed at the sprouting of the potato seedlings – 132.4–209.9 gm^{-2}.

This could be explaind by the short vegetation period, which was interrupted by mechanical soil loosening. The deeper the tillage, the smaller was the infestation of weeds in the potato crops. This was confirmed by the inverse correlation dependence of the average force between the depth of ploughing and the amount and weight of weeds r=-0.68–0.66.

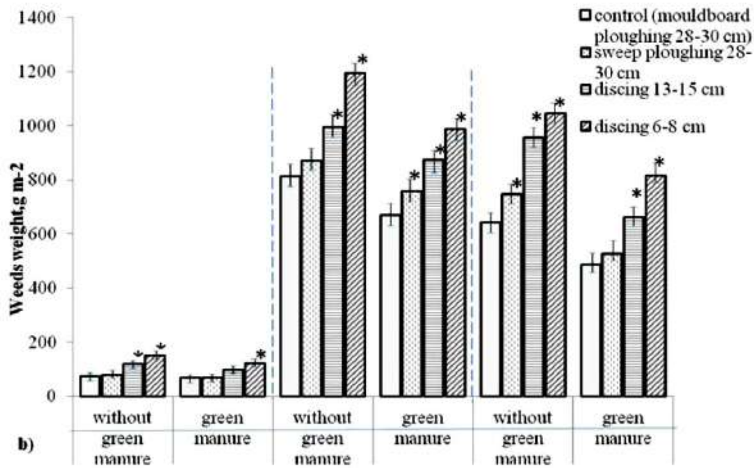


Figure 4.23 – Impact of green manure and soil tillage on the dynamics of amounts and weight of weeds in potato crops (Mishchenko et al.m, 2019)

Reducing the amount and weight of weeds during the potato's growing season had the largest effect on methods that involve an application of green manure in addition to the use of mouldboard ploughing and sweep ploughing at the same depth of 28–30 cm. The inverse correlation between application of green manure phytomass and the amount and weight of weeds in the potato crops was within r=-0.76 and -0.75, -0.59 and -0.55, respectively. Discing at the depths 13–15 cm and 6-8 cm was less effective in reducing the amount and weight of weeds; the proportion of the effect of phytomass green manure was 54–48 and 17–12%. The use of oil radish as incorporated green manure significantly decreased the number of biological groups of weeds and their mass during the potato growing period (Table 4.23).

The use of green manure cover crop effectively reduced the amount and weight of early and late spring weeds during the cultivation of potatoes – by 5.0–5.8 plants m^{-2} and 51.3–96.9 g m^{-2}, respectively, and the difference with the method without green manureby wintering weeds was the smallest – 0.9–1.5 plants m – 2 and 8.3–23.6 gm^{-2}.

Replacing conventional ploughing with sweep ploughing and disk ploughing led to an increase in the weed infestation in the potato crop, primarily in the early spring group – 3.8–12.4 plants m^{-2} and 57.9–184.1 gm^{-2} respectively. There was an insignificant change in the amount and weight of the late spring and perennial weeds when usings weep ploughing at a depth of 28–30 cm. Discing at 13–15 cm caused an insignificant increase in the amount of perennial weeds, compared with mouldboard ploughing. The amount and weight of all biological groups of weeds significantly increased in both nutrients backgrounds under discing at 6–8 cm.

The application of oilseed radish as green manure contributed to a significant reduction in the amount of weed seeds in the root soil layer at a depth of 0–30 cm to 3.3–4.0 million plants ha^{-1}during the potato growing period; the reduction in potential weed infestation is not significant; only in the 20–30 cm deepsoil layerunder sweep and discing (Table 4.24).

Table 4.23

Distribution of biological groups of weed in agrocenosis Solanum tuberosum (x ± SE, n=15) (Mishchenko et al.m, 2019)

Treatment Green manure incorporation	Tillage system	Biological group of weeds			
		Early spring	Late spring	Wintering	Pirennial
		Amount of weeds, plant m^2			
Without green manure	control (mouldboard ploughing 28–30 cm)	13.7 ± 0.92	15.9 ± 0.44	2.6+ 0.24	2.2+ 0.22
	sweep ploughing 28–30 cm	18.3 ± 1.02*	16.2 ± 1.22	3.0 ± 0.12*	2.1 ± 0.16
	discing 13–15 cm	22.8 ± 0.88*	18.3 ± 0.90*	4.0 ± 0.12*	2.6 ± 0.44
	discing 6–8 cm	26.1 ± 0.89*	19.9 ± 1.06*	5.1± 0.52*	3.5 ± 0.47*
Green manure of oilseed radish	control (mouldboard ploughing 28–30 cm)	8.7 ± 1.08	7.9 ± 0.76	1.73± 0.21	1.7 ± 0.25
	sweep ploughing 28–30 cm	12.5 ± 0.58*	7.1 ± 0.82	1.5 ± 0.36	1.3 ± 0.24
	discing 13–15 cm	17.5 ± 0.92*	9.4 ± 0.94*	2.6 ± 0.28*	1.9 ± 0.32
	discing 6–8 cm	20.5 ± 1.11*	12.3 ± 1.06*	3.3 ± 0.22*	2.7 ± 0.34*
		Weight of weeds, g m^2			
Without green manure	control (mouldboard ploughing 28–30 cm)	196.0 ± 9.6	298.2 ± 10.2	25.5 ± 2.5	47.9 ± 1.2
	sweep ploughing 28–30 cm	253.9 ± 8.4*	302.1 ± 11.6	34.4 ± 1.8*	48.4 ± 1.5
	discing 13–15 cm	328.4 ± 10.6*	350.7 ± 6.3*	45.1 ± 1.4*	65.3 ± 2.0*
	discing 6–8 cm	380.1 ± 8.6*	373.1 ± 6.5*	53.2 ± 2.1*	77.9 ± 3.2*
Green manure of oilseed radish	control (mouldboard ploughing 28–30 cm)	133.3 ± 9.0	237.1 ± 9.2	17.2 ± 2.0	21.7 ± 1.0
	sweep ploughing 28–30 cm	202.6 ± 8.4*	248.72 ± 8.5*	14.4 ± 3.4	21.5 ± 2.5
	discing 13–15 cm	247.4 ± 8.6*	265.3 ± 9.8*	24.6± 3.1*	32.4 ± 0.7*
	discing 6–8 cm	283.2 ± 9.3*	280.9 ± 10.2*	29.6± 3.8*	45.5 ± 2.2*

*significant at *p<0.05*

Table 4.24

Potential weed propagation on harvest potato time, million pcs ha^{-1} (x ± SE, n=10) (Mishchenko et al.m, 2019)

Treatment		Soil layer, < cm								Total
Green manure incorporation	**Tillage system**	**0-5**		**5-10**		**10-15**		**20-30**		
Without green manure	control (mouldboard ploughing 28–30 cm)	19.9	±	18.2	±	36.0	±	30.3	±	104.4
		1.01		1.04		0.56		0.65		
	sweep ploughing 28–30 cm	23.5	±	33.8	±	25.0	±	21.6	±	103.9
		0.98		1.81*		0.36*		0.52		
	discing 13–15 cm	24.4	±	34.8	±	23.4	±	21.4	±	104
		0.90		0.96*		0.45*		0.50		
	discing 6–8 cm	26.9	±	33.6	±	22.1	±	21.2	±	103.8
		1.0*		2.00*		0.86*		0.8*		
Green manure ofoilseed radish	control (mouldboard ploughing 28–30 cm)	18.7	±	17.7	±	35.1	±	29.6	±	101.1
		0.97		1.52		0.74		0.38		
	sweep ploughing 28–30 cm	22.3	±	32.5	±	24.1	±	21.3	±	100.2
		0.82		1.22*		0.44*		0.44		
	discing 13–15 cm	23.1	±	34.0	±	22.1	±	21.1	±	100.3
		0.74		1.20*		0.26*		0.81		
	discing 6–8 cm	25.3	±	32.0	±	21.6	±	20.9	±	99.8
		1.01		1.35*		0.33*		0.74		

significant at *$p<0.05$*

Between the phytomass of radish oilseed and the amount of weed seeds from all methods of soil tillage a close-to-value strong inverse correlation dependencies was found-r=-0.76–0.7 with probability 70–76 %.

Tillage without soil overturning also contributes to reducing the total amount of weed seeds in the soil layer 0–30 cm deep. But the difference in the potential weed infestation compared with mouldboard ploughing was significant by discing 6-8 cm, conducted in conjunction with the application of oilseed radish green manure and was 1.3 million plants per hectare. As the soil layers 0–30 cm are not intensively mixed when using sweep ploughing and discing, a significantly smaller amount of weed seeds were observed compared with the mouldboard ploughing technique in soil layers 10–20 cm deep – by 11.0–13.9 million psc. ha^{-1} and 20–30 cm – at 8.3–9.1 million psc. ha^{-1} for both backgrounds. Using ploughless tillage contributes to a concentration of substantially larger amounts of weed seeds in the upper layers – 0-5 and 5–10 cm deep to 3.6–7.0 and 14.316.6 million psc.ha^{-1}, respectively.

A close inverse correlation was determined between the increase of the depth of tillageand the amount and weed seeds in the soil layer 0–10 cm deep (r=-0.71), and the straight line correlation was set in the lower layers 10–20 and 20–30 cm deep (r=0.96, and 0.64).

Tillage impact on the actual weed infestation of potatoes crop was in range 34-46% and has to be said the influence of different methods of tillage on the amount of weeds was larger than on its weight (Figure 4.24).

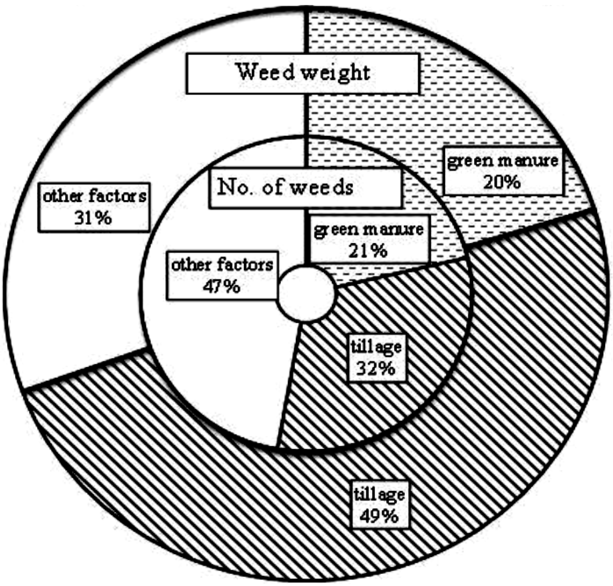


Figure 4.24 – Impact fraction of green manure and method of tillage on weed infestation in potato crops (Mishchenko et al.m, 2019)

Green manure made from oilseed radish plants also had a higher impact on the number of weeds-39% than its weight – 29%. The primary tillage technique had the largest impact on the potential weed infestation in the layer 10–20 cm deep (66.4%), and the least – 0–10 cm deep (46.1%). But method of application of green manure from oilseed radish had a larger impact on the potential weed infestation of the entire soil root layer 0–30 cm deep than the different methods of tillage. The green manure incorporation had a larger effect on the number of weed seeds in the upper soil layer- 0.81% more than in the deep layers – 0.43 and 0.2% (Figure 4.25).

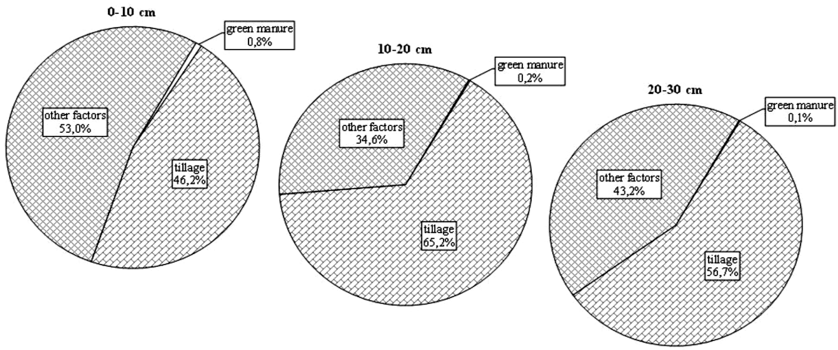


Figure 4.25 – Impact fraction of tillage and oilseed radish incorporating on the potential weed infestation in the soil layers 0-30 cm (average for 2006-2010). (Mishchenko et al.m, 2019)

The growth of the smallest amount of weeds produced the highest yields of 30.3 t ha^{-1} using the green manure application method and ploughless tillage method 28–30 cm deep (Figure 4.26).

Reducing the depth of plougless tillage and the non-application of green manure significantly reduced the yield of potato tubers-by 1.8–5.1 tha^{-1}, and 3.9–6.2 t ha^{-1}, respectively.

Based on the of herbological monitoring of potato crops, the most effective method of weed control is using green manure made from oilseed radish incorporation in addition to sweep ploughing at a depth of 28–30 cm. Using these methods, potential weed infestation in the soil layer 0–30 cm deep has been reduced overall, and the smallest amount of weed seeds was observed in the soil layer 0–10 cm deep, compared with other ploughless treatments. Quantitatively-weighed weed infestation under sweep ploughing was similar to the mouldboard ploughing method. The highest potato tuber yield 30.3 t ha^{-1} was obtained under the incorporation of oilseed radish green manure and using of sweep ploughing at 28–30 cm deep.

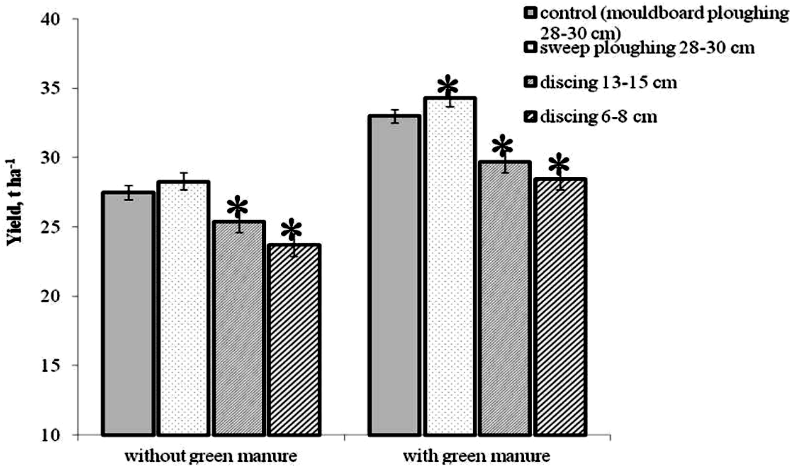


Figure 4.26 – Influence of green manure incorporation and methods of tillage on potatoes yield, t ha^{-1} (average for 2006-2010). *-significant at $p<0.05$ (Mishchenko et al.m, 2019)

Similar results were obtained in the study by Sturm et al. (2017). For the two treatments, where oilseed radish was sown before the winter wheat harvest (3 WBH and 5 WBH), oilseed radish cv. Farmer was sown in the pre-existing winter wheat crop with 25 kg ha^{-1} of coated seeds (149 seeds m^{-2}) (Feldsaaten Freudenberger, Krefeld, Germany) with a pneumatic fertilizer spreader (Aero, Rauch Landmaschinen GmbH, Sinzheim, Germany). The oilseed radish coat consisted of different layers containing humic acid, lime, plant strengthening agents and protection layers. Coated oilseed radish seeds were developed to allow an optimum cover crop emergence and growth. The increased seed weight compared to conventional seeds allows an increased flight distance and more homogeneous sowing, while sowing with a pneumatic fertilizer. The included humic acids, plant strengthening agents (Biplantol®), lime for the pH regulation and the increased water storage can improve the oilseed radish germination and development. For treatments sown at harvest (H), one (1 WAH) and three (3 WAH) weeks after harvest, a flat stubble cultivation (4 cm) (Dyna Drive, Bomford, Worcestershire, UK) was performed prior to sowing. Then un-coated oilseed radish cv. Farmer was sown in 2 cm depth with 25 kg seeds ha^{-1} (198 seeds m^{-2}) with a pneumatic sowing machine (D82, Agrarmarkt Deppe GmbH, Bad Lauterberg, Germany). Calcium-ammonium-nitrate (27% N, 2% S) fertilizer was applied in half of the plots (Aero, Rauch Landmaschinen GmbH, Sinzheim, Germany) at cover crop sowing dates with 45 kg N ha^{-1} (N_{45}). Two controls with no cover crop sowing (NCC) and fertilization (N_0) were included. Predominant weed species were *Alopecurus myosuroides* Huds. (11% and 16%), *Veronica pérsica* Poir. (14% and 18%), *Matricaria chamomilla* L. (8% and 10%), *Lamium purpureum* L. (24% and 2%), *Galium aparine* L. (10% and 5%) and *Volunteer wheat* (31% and 46%) in the untreated controls in 2015 and 2016, respectively. Cover crop and weed biomass were measured by harvesting two 0.25 m^2 quadrats within each plot at 7 WAH and 12 WAH. Collected biomass was washed and dried in a drying chamber at 80°C for 48 h. The reductions of weed density, cover crop and weed dry biomass were calculated, relative to the untreated control.

Table 4.25

Different oilseed radish treatments and sowing dates of the field experiments in two experimental years (Sturm et al., 2017)

Treatment	Sowing date	2015	2016
No cover crop (NCC)	no cover crop	-	-
5 WBH (weeks before harvest)	five weeks before winter wheat harvest	June 29^{th}	July 6^{th}
3 WBH	three weeks before winter wheat harvest	July 13^{th}	July 20^{th}
Harvest (H)	at winter wheat harvest	August 3^{rd}	August 10^{th}
1 WAH (weeks after harvest)	one week after winter wheat harvest	August 11^{th}	August 17^{th}
3 WAH	three weeks after winter wheat harvest	August 24^{th}	August 31^{th}

In 2015, oilseed radish biomass ranged from 5.6 to 4083.2 kg ha^{-1} measured at 7 WAH and 12 WAH (Table 4.25). The highest crop biomass was achieved in treatment 1 WAH at 7 WAH (100 kg ha^{-1}) and 12 WAH (3069 kg ha^{-1}), respectively. The highest weed biomass was measured in treatment NCC (73 kg/ha) and treatments 5 WBH (81 kg ha^{-1}) and 3 WBH (163 kg ha^{-1}) at 7 WAH and 12 WAH. The highest weed control efficacy was achieved by treatment 1 WAH with 89% and 80% at 7 WAH and 12 WAH across both fertilization levels (N_0 and N_{45}), respectively.

Reversed oilseed radish biomass was measured among all sowing treatments in 2015 compared to 2016. In 2015, the highest biomass was measured in treatment 1 WAH compared to 5 WBH and 3 WBH in 2016. This could be contributed to insufficient precipitation, which resulted in unfavourable field conditions for cover crop germination and growth at the early beginning (Table 4.26). The lower precipitation (-55%) with higher mean temperature (+11%) in 2015 during the vegetation period of treatments 5 WBH and 3 WBH led to lower oilseed radish germination, which resulted in a reduced biomass production in 2015 compared to 2016. Especially in 2016, the treatments 5 WBH and 3 WBH provided high weed suppression, due to the early sowing and fast oilseed radish development under favorable field conditions. Moreover, the similar oilseed radish biomass in treatments 5 WBH (2238 kg ha^{-1}) and H (2081 kg ha^{-1}) showed different weed control efficacies at 12 WAH, which can be attributed to an earlier light interception due to a faster soil coverage and weed shading. After wheat harvest, the stubble area was already covered with the cover crop. This growth advantage compared to weeds led to higher weed suppression, especially in the pre-harvest treatments (5 WBH and 3 WBH) in 2016. It was found a linear relationship between weed and cover crop biomass in 2015 (Table 4.27). In the following year, no significant correlation was calculated at 7 WAH and 12 WAH without fertilization.

Further, it was observed a linear relationship between weed biomass and density in 2016 ($R^2 = 0.4406$, $P < 0.05$), however this relationship was much weaker and not significant in 2015 ($R^2 = 0.252$). It is assumed that the competition of the weeds with the cover crop biomass played a major role in weed biomass suppression in 2015. In 2016, weed emergence, which illustrates weed density, was highly suppressed by the cover crop and consequently reduced the weed biomass. Beside competitive effects of oilseed radish on the overall weed suppression, the family of Brassicaceae is well documented for the active and passive release of allelochemicals, as isothiocyanates, in the environment.

Table 4.27

Dry biomass of oilseed radish and weeds without (N0) and with (N45) fertilization 7 and 12 weeks after harvest (WAH) across all treatments in 2015 and 2016 (Sturm et al., 2017)

Year	Date	Treatment	Oilseed radish biomass (kg/ha)		Weed biomass	(kg/ha)
			N_0	N_{45}	N_0	N_{45}
2015	7 WAH	NCC	0^{bA}	0^{bA}	82^{abA}	62^{abA}
		5 WBH	6^{bA}	10^{bA}	85^{aA}	82^{aA}
		3 WBH	18^{bA}	20^{bA}	76^{abA}	68^{abA}
		H	56^{abA}	35^{abA}	28^{bcA}	44^{abA}
		1 WAH	100^{aA}	128^{aA}	10^{cA}	6^{bA}
		3 WAH	29^{abA}	24^{bA}	34^{abcA}	42^{abA}
	12 WAH	NCC	0^{cA}	0^{bA}	78^{abA}	70^{abcA}
		5 WBH	439^{bA}	436^{bA}	83^{abA}	74^{abA}
		3 WBH	1501^{abA}	637^{bA}	88^{aA}	94^{aA}
		H	1563^{abA}	1412^{abA}	29^{bcA}	63^{abcA}
		1 WAH	3069^{aA}	4083^{aA}	9^{cA}	21^{cA}
		3 WAH	827^{bA}	1532^{abA}	40^{abcA}	42^{bcA}
2016	7 WAH	NCC	0^{cA}	0^{cA}	328^{aA}	223^{aA}
		5 WBH	1883^{aA}	2247^{aA}	11^{bA}	24^{bA}
		3 WBH	1115^{abB}	1995^{aA}	19^{bA}	41^{bA}
		H	906^{abA}	1764^{abA}	68^{bA}	26^{bA}
		1 WAH	410^{abA}	242^{bcA}	30^{bA}	8^{bA}
		3 WAH	81^{bA}	131^{cA}	15^{bA}	32^{bA}
	12 WAH	NCC	0^{cA}	0^{bA}	721^{aA}	1142^{aA}
		5 WBH	1760^{aB}	2715^{aA}	6^{cA}	9^{bA}
		3 WBH	962^{abB}	1353^{aA}	4^{cA}	8^{bA}
		H	1583^{aA}	2579^{aA}	139^{abA}	44^{bA}
		1 WAH	630^{abA}	1215^{aA}	105^{abA}	45^{bA}
		3 WAH	383^{bB}	1216^{aA}	60^{bcA}	51^{bA}

Lowercase letters are used to compare the oilseed radish and weed biomass among the different treatments and the uppercase letters are used to compare the oilseed radish and weed biomass between the two fertilization levels (N_0, N_{45}). Means with identical letters within the table do not differ significantly based on the Tukey's *HSD* (honest significant difference) test ($P < 0.05$); NCC – no cover crop; WBH – weeks before harvest; H – harvest

The weed density varied between 9 and 202 plants m^{-2} across the experimental years 2015 and 2016. In 2015, the highest weed density reduction of the monocotyledons, dicotyledons and volunteer wheat was observed in treatments H and 1 WAH with 72, 65, 69 and 83, 86, 80%, respectively, compared to NCC across both measurement dates and fertilization levels (Figure 4.27).

In the following year, the weed density was reduced by all treatments compared to the untreated control. The most effective weed control efficacy was achieved by treatments 3 WBH and 5 WBH with up to 91, 84, 83 and 86, 90, 85% on monocotyledons, dicotyledons and volunteer wheat compared to NCC at 12 WAH, respectively (Figure 4.28). Effective weed density reductions by fall-sown cove

Table 4.28

Coefficients of determination of the Pearson's correlation between cover crop (kg ha^{-1}) and weed (kg/ha) biomass (Sturm et al., 2017)

Year	Date	N_0	N_{45}
2015	7 WAH 12 WAH	-0.6134*** -0.5954***	-0.3111** -0.4481***
2016	7 WAH 12 WAH	-0.1127^{ns} -0.0988^{ns}	-0.1685* -0.3655**

**P < 0.05; **P < 0.01; ***P < 0.001*; ns – not significant; WAH – weeks after harvest

In both years, there was no significant interaction between the factors fertilization and sowing date on cover crop and weed biomass and weed density. Cover crop fertilization did not demonstrate any changes on oilseed radish and weed biomass 7 WAH and 12 WAH in 2015 (Table 4.28). The low effects of the fertilization can be attributed to exceptional weather conditions in 2015 with low precipitation during the experimental period (Table 4.26). Water shortage and the C:N ratio increased by wheat straw decomposition can decrease nitrogen availability for cover crop plants within the field. Furthermore, an increased duration and intensity of drought are associated with a decreased N mineralization into the soil.

In the following year, the oilseed radish biomass was significantly increased by 54, 41 and 218% in treatments 5 WBH, 3 WBH and 3 WAH, respectively, at 12 WAH due to fertilization. The soil sample observation measured an Nmin content of 20.9 kg N ha^{-1} (0–90 cm) at the beginning of the experiment. The increased biomass can be attributed to the missing soil nutrients after 7 WAH. No differences were detected for weed biomass between N_0 and N_{45} at 7 WAH and 12 WAH. Furthermore, higher nutrient uptake efficacy and the influence of allelopathic compounds by cover crops can lead to lower effects of fertilization on weed growth.

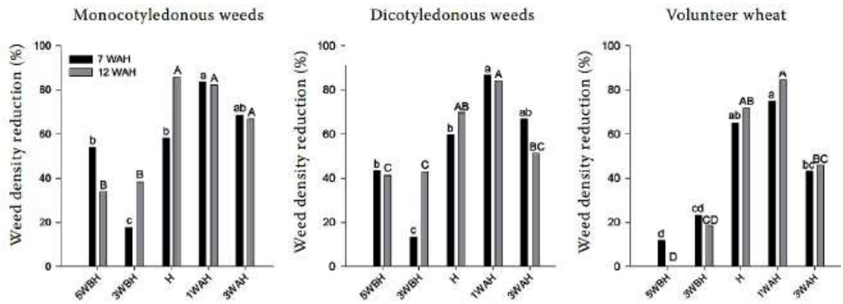


Figure 4.27 – Weed density reduction (%) of monocotyledonous and dicotyledonous weeds and volunteer wheat (*Triticum aestivum*) at five different sowing dates of oilseed radish cover crop measured at 7 WAH (weeks after harvest) and 12 WAH in 2015. Means with identical letters within the table do not differ significantly based on the Tukey's HSD (honest significant difference) test (*P < 0.05*); WBH – weeks before harvest; H – harvest (Sturm et al., 2017)

The fertilization of the oilseed radish revealed insignificant changes in weed density in both years.

Different weeds are able to compensate a constant or reduced weed density by higher biomass production per plant.

This study (Sturm et al., 2017) assumed that the weed suppressive ability of coated oilseed radish cover crops depends on sufficient precipitation for germination and growth. Further studies should be conducted to proof the influence of the soil water availability on cover crop and weed biomass accumulation. An early cover crop sowing can provide higher cover crop biomass and increased weed control efficacy as observed in 2016. The use of coated cover crops combined with a pre-harvest sowing can prolong the cover crop vegetation period in the field, reduce the workload peaks during and after winter wheat harvest and suppress weeds more effectively compared to conventionally sown cover crops. More research with further coated cover crops needs to be conducted to investigate the full potential of a prolonged cover crop vegetation period.

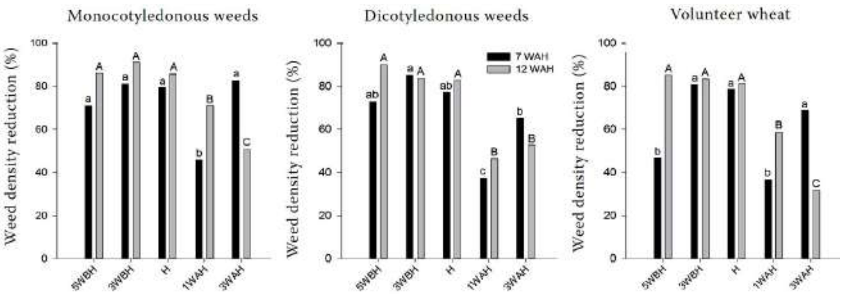


Figure 4.28 – Weed density reduction (%) of monocotyledonous and dicotyledonous weeds and volunteer wheat (*Triticum aestivum*) at five different sowing dates of oilseed radish cover crop measured at 7 WAH (weeks after harvest) and 12 WAH in 2016. Means with identical letters within the table do not differ significantly based on the Tukey's HSD (honest significant difference) test (*P* < *0.05*); WBH – weeks before harvest; H – harvest (Sturm et al., 2017)

Important from the point of view of green manure and biofumigation application of oil radish is its resistance to the action and aftereffects of herbicides, which is important from the point of view of its long-term use in crop rotation. Thus, in the studies of Brooker et al. (2019) In the PRE field experiment (Table 4.29), the Group 2 herbicides flumetsulam and rimsulfuron caused the greatest reduction (>70%) in oilseed radish stand at both interseeding timings (Table 4.30). When oilseed radish was interseeded into corn at the V3 stage, applications of mesotrione, pyroxasulfone, and acetochlor also resulted in reduced stands, whereas at the V6 stage, pyroxasulfone and saflufenacil were the only other herbicides that caused a reduced stand compared with the no-herbicide control. In the greenhouse study, atrazine and mesotrione were the only PRE herbicides that caused a 50% reduction in oilseed radish biomass at rates that were less than field-use rates (Table 4.31). Herbicides applied PRE that reduced oilseed radish biomass by 10% at rates lower than field-use rates included atrazine, mesotrione, isoxaflutole, acetochlor, dimethenamid-P, flumetsulam, saflufenacil, and pyroxasulfone (Table 4.31). In the POST field experiment, the time ofinterseeding did not affect oilseed radish response to herbicides applied POST to V2 to V3 corn; therefore, data were combined over interseeding timings (Table 4.32). Applications of atrazine (1,120 g ha^{-1}), tembotrione, topramezone, mesotrione + atrazine (571 and 1,120 g ha^{-1}), thiencarbazone + tembotrione, and S-metolachlor + mesotrione + glyphosate all resulted in unacceptable oilseed radish stands. In the greenhouse study, none ofthe herbicides applied POST resulted in reduced oilseed radish biomass compared with the no-herbicide control (Table 4.33); however, slight bleaching symptoms (<10%) were observed when any of the Group 27 herbicides (mesotrione, tembotrione, or topramezone) were applied (data not shown).

Table 4.29

PRE and POST herbicide common name, application timings, herbicide sites of action (SOA), and field use rates applied in the field and greenhouse experiments from 2016 to 2018 (Brooker et al., 2019)

Common name	Trade name	Application timing	SOA	Rate (g ai ha^{-1})
1	2	3	4	5
Flumetsulam	Python[a]	PRE	2	56
Rimsulfuron	Resolve SG[a]	PRE	2	22
Clopyralid	Stinger[a]	PRE	4	105
Atrazine	AAtrex[b]	PRE, POST (0.5X, 1X)[g]	5	1,120, 571, 1,120
Saflufenacil	Sharpen[c]	PRE	14	75
Acetochlor	Harness[d], Warrant[d]	PRE, POST	15	2,455, 1,262
Dimethenamid-P	Outlook[c]	PRE	15	942
Pyroxasulfone	Zidua[c]	PRE	15	179
S-metolachlor	Dual II Magnum[e]	PRE	15	1,424
Bicyclopyrone	comp. of Acuron[e]	PRE	27	50
Isoxaflutole	Balance Flexx[d]	PRE	27	105
Mesotrione	Callisto[e]	PRE, POST	27	210, 105
Bromoxynil	Buctril[d]	POST	6	421
Fluthiacet	Cadet[f]	POST	14	1.7

(End of Table 4.29)

1	2	3	4	5
Tembotrione	Laudis[d]	POST	27	92
Topramezone	Armezon[c]	POST	27	18
Mesotrione + atrazine	-	POST (0.5X)[g]	27 + 5	105 + 285
Mesotrione + atrazine	-	POST (1X)[g]	27 + 5	105 + 509
Dicamba + diflufenzopyr	Status[c]	POST	4 +19	140 + 56
Dimethenamid-P + topramezone	Armezon PRO[c]	POST	15 + 27	920 + 17
Thiencarbazone + tembotrione	Capreno[d]	POST	2 + 27	27 + 77
S-metolachlor + mesotrione + glyphosate	Halex GT[e]	POST	15 + 27 + 9	1,068 + 105 +1,042

[a]Corteva Agriscience, Wilmington, DE, https://www.corteva.com; [b]Land O'Lakes, Inc., Arden Hills, MN, https://www.landolakesinc.com; [c]BASF Corporation, Florham Park, NJ, https://www.basf.com; [d]Bayer CropScience LP, St. Louis, MO, https://www.cropscience.bayer.com; [e]Syngenta International AG, Basel, Switzerland, https://www.syngenta.com; [f]FMC Corporation, Philadelphia, PA, http://www.fmc.com; [g]Applied at different field use rates as indicated.

Table 4.30

Annual ryegrass and oilseed radish stand reduction (%) caused by PRE herbicides in the field experiment (Brooker et al., 2019)

Herbicide	Site of action	Annual ryegrass[2]	Oilseed radish[b]	
		V3 + V6	V3	V6
Stand reduction (%)				
Flumetsulam	2	46*	74*	100*
Rimsulfuron	2	33*	73*	74*
Clopyralid	4	6	12	29
Atrazine	5	8	13	18
Saflufenacil	14	4	23	36*
Acetochlor	15	67*	44*	7
Dimethenamid-P	15	71*	28	6
Pyroxasulfone	15	86*	48*	41*
S-metolachlor	15	68*	27	9
Bicyclopyrone	27	7	6	16
Isoxaflutole	27	6	28	16
Mesotrione	27	17*	56*	15
No herbicide		0	0	0
±SEM[d]		(± 8)	(± 10)	(± 10)

[a]Annual ryegrass data are combined across site years and the V3 and V6 interseeding timings. [b]Oilseed radish data were combined over site years.[c]Treatment means followed by an asterisk (*) indicates significantly reduced cover crop stand compared with the no-herbicide control at a = 0.05 within each column using Fisher's least significant difference test. [d]Standard error of the mean.

Table 4.31

Annual ryegrass and oilseed radish stand reduction (%) caused by POST herbicides in the field experiment.[3] (Brooker et al., 2019)

Treatment	Site of Annual action	Ryegrass	Oilseed radish
Stand reduction (%)			
Atrazine (571 g ha^{-1})	5	14	20
Atrazine (1120 g ha^{-1})	5	12	34*
Bromoxynil	6	13	11
Fluthiacet	14	26*	19
Acetochlor	15	91*	24
Mesotrione	27	9	18
Tembotrione	27	60*	37*
Topramezone	27	76*	44*
Mesotrione + atrazine (285 g ha^{-1})	27 + 5	16	59*
Mesotrione + atrazine (509 g ha^{-1})	27 + 5	23*	60*
Dicamba + diflufenzopyr	4+19	48*	31
Dimethenamid-P + topramezone	15 + 27	76*	4
Thiencarbazone + tembotrione	2 + 27	87*	47*
S-metolachlor + mesotrione	15 + 27 + 9	92*	41*
+ glyphosate			
No herbicide		0	0
±SEM[c]		(±9)	(±12)

[a]Data are combined across site years and the V3 and V6 interseeding timings. [b]Treatment means followed by an asterisk (*) significantly reduced cover crop stand compared with the no herbicide control within each column at a = 0.05 using Fisher's least significant difference test. [c]Standard error of the mean.

Table 4.32

PRE herbicide rates to cause 10% biomass reduction (BR10) and 50% biomass reduction (BR50) using Equations 1 and 2 in the text to annual ryegrass, oilseed radish, and crimson clover in the greenhouse from 2016 to 2018 (Brooker et al., 2019)

Herbicide	Site of action	Field use rate g ai ha^{-1}	Annual	ryegrass	Oilseed radish		Crimson clover	
			BR10	BR50	BR10	BR50	BR10	BR50
			% of field use rate[a]					
1	2	3	4	5	6	7	8	9
Flumetsulam	2	56	>100	>100	18.3	>100	0.05	>100
Rimsulfuron	2	22	74.0	>100	>100	>100	89.3	>100

(End of Table 4.32)

1	2	3	4	5	6	7	8	9
Clopyralid	4	105	>100	>100	>100	>100	13.9	77.4
Atrazine	5	1,120	24.6	>100	20.0	86.1	1.9	7.7
Saflufenacil	14	75	>100	>100	0.04	>100	86.3	>100
Acetochlor	15	2,455	5.0	11.4	96.0	>100	0.3	7.8
Dimethenamid-P	15	942	3.0	9.3	0.01	>100	18.6	55.5
Pyroxasulfone	15	179	15.5	28.1	79.9	>100	88.5	>100
S-metolachlor	15	1,424	0.8	>100	>100	>100	1.7	24.2
Bicyclopyrone	27	50	>100	>100	>100	>100	0.01	>100
Isoxaflutole	27	105	79.6	>100	0.9	>100	81.0	93.8
Mesotrione	27	210	>100	>100	19.3	91.4	0.01	>100
[a]Rate of herbicide sprayed as a fraction of the field use rate.								

Table 4.33

Annual ryegrass, oilseed radish, and crimson clover aboveground biomass reduction caused by postemergence (POST) herbicides in the greenhouse (Brooker et al., 2019)

Herbicide	Site of action	Rate[a]	Annual ryegrass	Oilseed radish	Crimson clover
	Aboveground biomass (g pot^{-1})				
1	2	3	4	5	6
Atrazine (571 g ha^{-1})	5	0.5	0.49	1.25	0.23
		1	0.55	1.31	0.17*
Atrazine (1,120 g ha^{-1})	5	0.5	0.45	1.08	0.14*
		1	0.62	1.30	0.09*
Bromoxynil	6	0.5	0.71	1.45	0.36
		1	0.62	1.29	0.46
Fluthiacet	14	0.5	0.77	1.34	0.36
		1	0.73	1.42	0.49
Acetochlor	15	0.5	0.38	1.28	0.49
		1	0.30*	1.36	0.48
Mesotrione	27	0.5	0.59	1.14	0.39
		1	0.51	1.12	0.29
Tembotrione	27	0.5	0.52	1.28	0.43
		1	0.51	1.19	0.31
Topramezone	27	0.5	0.56	1.30	0.39
		1	0.67	1.50	0.42
Mesotrione + atrazine (285 g ha^{-1})	27 + 5	0.5	0.57	0.86	0.38
		1	0.67	1.23	0.42

(End of Table 4.33)

1	2	3	4	5	6
Mesotrione + atrazine (509 g ha^{-1})	27 + 5	0.5	0.68	1.12	0.37
		1	0.49	1.17	0.37
Dicamba + diflufenzopyr	4+19	0.5	0.58	1.03	0.21
		1	0.35	1.27	0.14*
Dimethenamid-P + topramezone	15 + 27	0.5	0.31*	1.45	0.28
		1	0.24*	1.21	0.14*
Thiencarbazone + tembotrione	2 + 27	0.5	0.47	1.35	0.28
		1	0.55	1.04	0.23
S-metolachlor + mesotrione + glyphosate	15 + 27 + 9	0.5	0.15*	1.26	0.22
		1	0.11*	1.13	0.11*
No herbicide			0.63	1.56	0.34
±SEM[c]			(±0.20)	(±0.83)	(±0.14)

[a]Rate of herbicide sprayed as a fraction of the 1x rate; [b]Treatment means followed by an asterisk (*) indicates significantly reduced cover crop biomass compared with the no-herbicide control within each column at a = 0.05 using Fisher's least significant difference test. [c]Standard error of the mean.

Oilseed radish can be interseeded into corn at the V3 or V6 growth stages following PRE application of clopyralid, S-metolachlor, or bicyclopyrone. In the field experiments, atrazine and isoxaflutole also did not reduce oilseed radish stand, but when these herbicides were applied in the greenhouse experiment closer to oilseed radish seeding, at least 10% biomass reduction occurred. Additionally, isoxaflutole degradation is accelerated in biologically active soils. Greenhouse soils in this experiment were sterilized, so degradation was likely slowed. Delaying oilseed radish interseeding until corn is at the V6 growth stage may reduce injury and biomass reduction if acetochlor, dimethenamid-P, or mesotrione are applied. In this experiment, there was variability in oilseed radish injury following a saflufenacil application, with more injury occurring at V6 compared with V3. Seeding oilseed radish at either V3 or V6 following an application of saflufenacil likely causes some stand reduction, but this may be acceptable if weeds are controlled. Oilseed radish can be interseeded into V3 or V6 corn following POST applications of atrazine (571 g ha^{-1}), bromoxynil, fluthiacet, acetochlor, mesotrione, dicamba + diflufenzopyr, and dimethenamid-P + topramezone.

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CHAPTER 5. POTENTIAL OF OILSEED RADISH AS A BIOENERGY CROP

5.1. Oilseed radish as a raw material for biofuel production

The development of bioenergy is also very relevant for Ukraine with its significant potential of local fuels available for energy production – biomass up to 24 million tons of equivalent fuel per year. Oilseeds from the cabbage family are important in this area. Most monographic publications, perspective programs for agricultural development in Ukraine and foreign countries assign oilseed radish a promising role in ensuring bioenergy security both in terms of biofuel production and processing of its leaf mass through biochemical fermentation to produce biogas (Table 5.1).

Table 5.1

Potential productivity of oilseeds of the cabbage family – raw materials for phytodiesel (Tsytsiura, 2011)

Agricultural crops	Seed yield, t ha^{-1}	Oil content, %
Rapeseed		
winter	1.5–4.5	45–50
spring	1.3–3.5	41–49
Oilseed radish	1.2–2.1	31–50
Barbaréa vulgáris		
winter	1.5–2.5	43–47
spring	1.0–2.0	38–48
Mustard		
white	1.0–2.2	35–47
gray	1.2–2.1	32–49
Camelina spring	0.6–2.9	33–41

One of the most promising areas in Ukraine's non-conventional energy sector is the use of phytodiesel and phytomass (Strategic directions, 2020). It is known that the seeds of high-oil crops (rapeseed, rape, mustard, flax and oil radish, safflower, chufa, camelina) are one of the most promising sources of alternative biodiesel based on the classification of oilseeds (Figure 5.1).

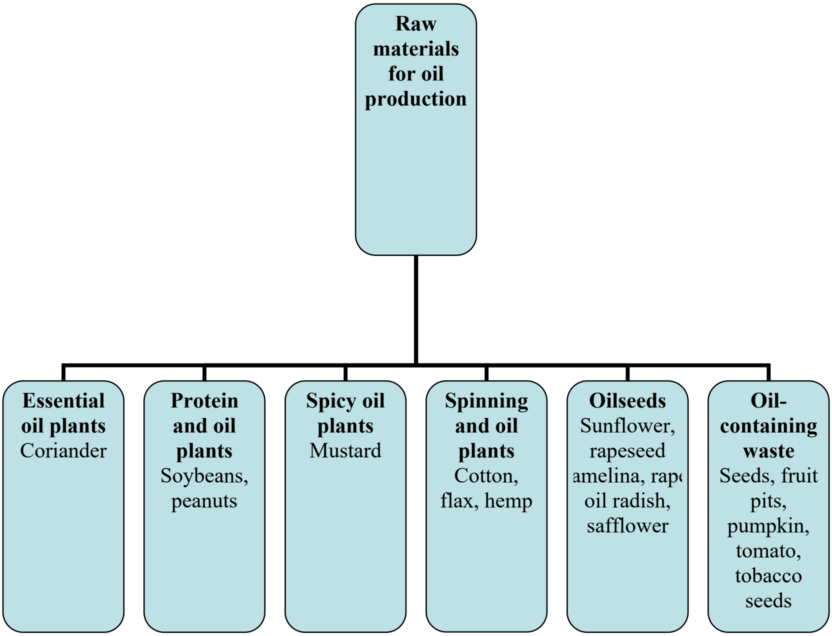


Figure 5.1 – Classification of oilseeds (Polischuk, 2010)

To date, Ukraine has created a collection of energy plants that includes about 350 taxa, and three areas of phytopower have been identified. The first area is feedstock crops based on highly productive, mostly perennial plants that provide phytomass for processing into solid biofuels or biomass or some other fuel, such as pyrolysis fuel. This group includes sorrel, perennial sida (up to 20 years old), whole-leaved silybum, elephant grass, perennial sorghum, etc. In total, this group includes 144 taxa. These include species, forms, and varieties of various crops.

The second large group includes crops that are selected in such a way that they are all high-oil crops. This includes 139 taxa. Among them are oil radish, winter and hybrid rape, camelina, etc. The third group includes plants used to produce phytoethanol – 71 taxa in total. These are sugar-containing plants, such as sugar sorghum, eucalyptus, chumizu, bubble sunflower or topin sunflower (a hybrid of sunflower and Jerusalem artichoke), etc.

If we make a comparative assessment of various oil-containing crops that can potentially be used for biofuel production (Figure 5.2), among 34 crops whose oil is to some extent a raw material for its production, oilseed radish ranks 18th with a productivity of 668 l ha^{-1} of vegetable oil.

The first mention of oil radish as an oil plant in the official Soviet literature dates back to 1952 (Sharapov, 1952). Kovarsky (1952), who studied oil radish in the Kherson region and Moldova, noted that the costs of growing it were much lower than those of sunflower, and the oil yield was much higher. Its seed yield ranges from 10–15 to 20–30 c ha^{-1}, which, with a seed oil content of 40–50%, provides an oil yield of 0.5–1.0 t/ha.

The first thorough studies of oil radish oil were conducted in 1952–1955 by Cherep (1955). According to the results of her studies, oil radish oil resembles sunflower oil in appearance, has a mild taste and a light radish flavor. The author conducted an organoleptic evaluation of the oil of this crop, carried out qualitative reactions and elemental analysis, and determined its physical and chemical characteristics, which are presented in the Table. Based on the results of the presented data (iodine and radon numbers), the author classifies oil radish oil as a semi-drying oil. The low saponification number is explained by the presence of erucic acid in the composition. The determination of the fatty acid composition of the oil showed the following composition: saturated acids 12.16 %, unsaturated acids 87.84 %, of which linoleic acid 10.01 %, oleic and erucic acids (in total) 70.13 %.

For a more detailed characterization, the oil radish oil was subjected to thermal compaction (polymerization) (Table 5.2), which showed the relevant technical parameters of the oil's suitability for thermodynamic combustion processes in controlled pressure and temperature systems. These parameters were also confirmed during oxy-polymerization (heating of the oil with oxygen purge) of the oil with different degrees of heating (Table 5.3).

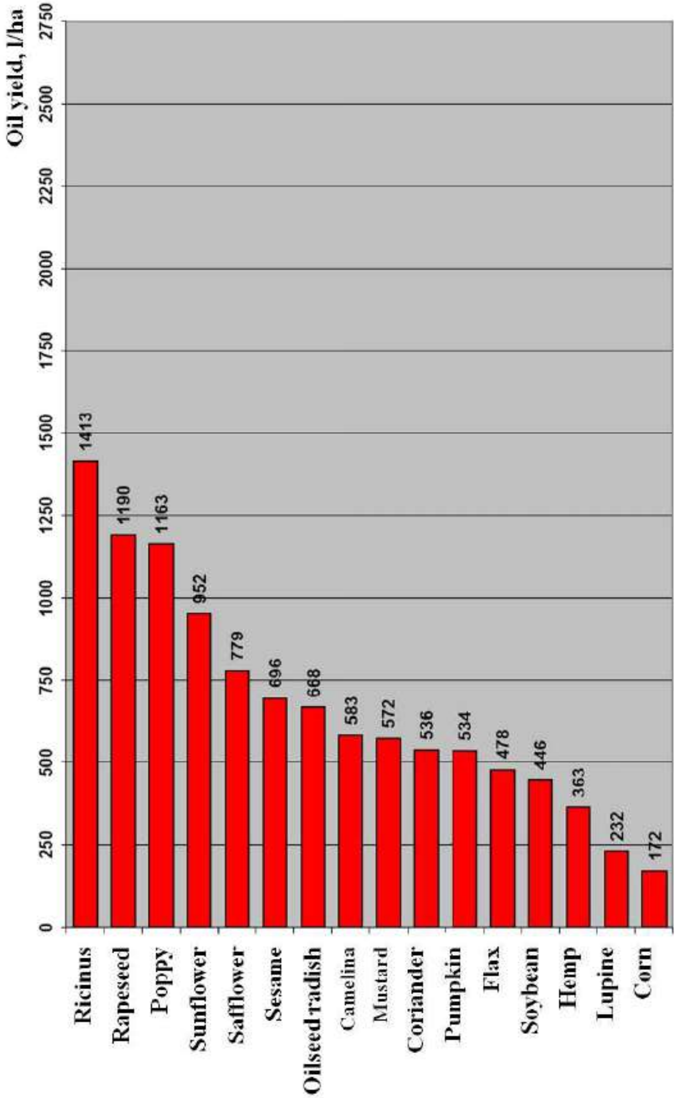


Figure 5.2 – Oil yield for different crops, liters/ha (Tsytsiura and Tsytsiura, 2015)

Table 5.2

Main characteristics of oil radish oil (Cherep, 1955)

Oil samples	Organoliptic properties				
	Colour	Transparency	Color on the iodine scale	Smell	Taste
Cold pressed oil	Golden yellowish	After settling, all samples are absolutely transparent	30	Light radish shade	Soft, satisfactory with a radish flavor
Hot pressed oil	Golden yellowish with a darker shade		40		
Oil extracted with ether	Golden yellowish with a darker shade		35		
Oil extracted with ether and washed with water	Golden yellowish with a greenish tint	–	–		
Oil extracted with gasoline	Golden yellowish with a darker shade	–	–		

Oil samples	After settling, all samples are absolutely transparent									
	Specific gravity at 20^0 C	Refractive index	Rotation of the polarization plane at 23 ^{0}C	Viscosity in degrees of Engler	Specific viscosity in centipoise	Relative surface tension	Critical dissolution temperature in absolute alcoho^{0}C	The temperature of solidification, ^{0} C	Brencken flash point	Solubility in organic solvents
Cold pressed oil	0.9153	1.4725	-0.75^0	3.91 (59^0)	69.33	0.4686	80	10	333^0	Well soluble in all organic solvents in 96 % alcohol only when heatedi
Hot pressed oil	0.9156	1.4725	–	3.99 (50^0)	70.90	0.4578	78	-17	320^0	
Oil extracted with ether	0.9159	1.4722	–	–	69.70	0.4509	79	–	–	
Oil extracted with ether and washed with water	0.91610	1.47220	–	–	74.33	0.4510	78	–	–	
Oil extracted with gasoline	0.9151	1.4722	–	–	73.52	0.4575	76	–	–	

(End of Table 5.2)

Oil samples	Chemical parameters								
	Acid number	Free acids in % per oleic acid	Saponification number	Airtime number	Iodine number	Rodan number	Amount of water-insoluble fatty acids (Genera number)	Amount of unsaponifiable substances	The amount of glycerin is calculated by the ether number
Cold pressed oil	0.9	0.45	171.4	170.5	100.5	81.96	93.80	1.20	9.33
Hot pressed oil	1.1	0.55	170.0	168.9	103.2	82.99	92.47	1.32	9.24
Oil extracted with ether	2.3	1.15	170.0	167.7	101.8	82.62	93.99	1.22	9.17
Oil extracted with ether and washed with water	2.3	1.15	170.6	168.3	102.5	80.35	92.21	1.22	9.21
Oil extracted with gasoline	2.1	1.05	170.0	167.9	100.8	81.60	92.51	1.62	9.18

Table 5.3

Physicochemical parameters of radish oil polymerized at a temperature of 280–300 0C (Cherep, 1955)

Oil samples	Heating time, h	The specific gravity d^{20}_{20}	Refractive index at 23 ^{0}C	Acid number	Free acids per oleic acid, %	Saponification number	Airtime number	Iodine number
Control	–	0.9150	1.4710	3.80	1.90	181.0	177.20	106.8
Heated oil	0.5	0.9182	1.4710	9.75	3.87	182.3	174.50	104.6
	2.5	0.9216	1.4715	14.30	7.15	184.0	169.70	98.0
	5.0	0.9261	1.4720	18.60	9.39	189.0	170.4	90.0
	7.5	0.9285	1.4730	21.74	10.87	191.4	169.66	84.6
	10.0	0.9299	1.4732	24.90	12.45	192.9	168.03	82.4
	12.0	0.9328	1.4733	26.30	13.15	189.3	163.0	71.7
	15.0	0.9342	1.4710	27.80	13.90	186.0	158.20	71.3
	17.5	0.9356	1.4750	30.81	15.40	184.8	153.99	65.3
	20.0	0.9374	1.4750	34.00	17.00	–	–	63.5
Control	0	0.9150	1.4730	3.49	1.75	178.5	175.01	106.8/0.13*
Oil blown with air at a temperature of 100–120 ^{0} C	5	0.9156	1.4731	3.50	1.75	178.7	175.2	104.2/0.41
	10	0.9229	1.4735	3.62	1.81	180.0	176.38	98.4/0.56
	15	0.9238	1.4740	3.75	1.88	181.5	177.75	97.5/0.99
	20	0.9316	1.4748	3.82	1.91	181.6	177.78	90.0/0.48
	25	0.9368	1.4752	4.13	2.07	181.7	176.57	81.0/–
	30	0.9443	1.4760	–	–	–	–	76.40/–
	35	0.9500	1.4772	4.80	2.40	189.5	181.7	72.1/0.34
	40	–	–	–	–	–	–	–/0.19
	50	–	–	–	–	–	–	сліди
Control	0	0.9150	1.4730	3.49	1.75	178.5	178.01	106.8/0.13*
Oil blown with air at a temperature of ратурі 130–150 ^{0} C	5	0.9152	1.4732	3.41	1.76	178.9	175.49	104.3/0.13
	10	0.9200	1.4738	3.45	1.73	181.6	178.15	92.5/0.16
	15	0.9256	1.4748	3.52	1.71	182.1	178.58	91.2/0.25
	20	0.9324	1.4758	3.63	1.82	182.3	178.67	83.93/0.39
	25	0.9402	1.4768	4.19	2.10	183.7	179.51	74.8/0.24
	30	0.9444	1.4778	4.94	2.47	192.2	187.26	64.6/0.16
	35	0.9582	1.4782	–	–	193.3	–	–
	40	0.9642	1.4794	7.22	3.61	201.2	193.98	52.2/0.09

*– peroxide number.

According to the results of such a comprehensive study of oil radish oil, Cherep, as part of the production implementation already in the period 1954–1955, confirmed the possibility of using the oil of this crop, which can act as an effective substitute for alizarin oil, which can be successfully used for skin fatting in the form of an emulsion of oil radish oil or its sulfated product. These conclusions allow us to recommend oil radish oil as a substitute for castor and alizarin oil for the fatty acidification of natural leather.

Today, the biofuel use of this crop oil is extremely promising. Ukraine, unfortunately, is only at the stage of actively starting to study this crop as a component of the biofuel market. Among the CIS countries, the Russian Federation, in particular the southern and central regions of the country, is a leader in this area. In European countries, the direction of using oil from oil radish for the production of alternative fuels is actively developed by Germany, Poland, and the UK, where varieties with high oil content in seeds are being created.

It should also be noted that oil radish forms a large phytomass, which in turn can be used as green manure and for fermentation to produce biogas. Between 2000 and 2024, its area in Europe and the United States (northern states) almost tripled compared to 1990. In particular, Landkom is actively engaged in growing oil radish in Europe and South Africa. In the United States, the center for the study of vegetable oil from radish is the state of Georgia (UGA College of Agricultural and Environmental Sciences).

The research of scientists at this institution notes that oil radish is an extremely promising non-food crop for the production of alternative fuels. The seeds of this crop contain 40-45% of vegetable oil, which is similar in chemical composition to rapeseed oil and has a wide range of economic uses, making it an excellent candidate for the biodiesel market.

These conclusions are confirmed by Shpaar (2006) and others (Moiseeva, 2006), noting that the technical direction of using its oil is determined by the content of simple unsaturated fatty acids (in % of the total fatty acid content – aicosene (8–11 %) oleic (23–36 %), erucic (9–30 %)), high content of saturated oleic acid (4–6 %), low content of multiple unsaturated linoleic (10–18 %) and linolenic (11–17 %) fatty acids (Tables 5.4–5.7, Figure 5.3).

It should be noted that in Ukraine, at present, the industrial processing of oil radish according to the "pressing – extraction" scheme for the production of technical oil is complicated by the lack of regulatory and technical documentation (DSTU, TU, etc.) for oil and meal made from it (Tsytsiura, 2011).

Table 5.4

Characteristics of oilseeds and fatty acid composition of oils (Polishchuk, 2010)

Crops	Botanical family	Variety type	Content, %		Fatty acid sweetness of oils, % to total fatty acid content							Glucosinolates content, µmol g^{-1}
			Fat	Protein	$C_{16:0}$ palmettine	$C_{18:0}$ stearic	$C_{18:1}$ oleic	$C_{20:1}$ aicosene	$C_{22:1}$ eruca	$C_{18:2}$ linoleum	$C_{18:3}$ linolenic	
Rape	Cruciferous	++	37 – 47	22 – 25	2	1	1	7	50	15	7	55 – 75
		00	39 – 48	22 – 25	3 – 5	1 – 2	58 – 62	0 – 1	0 – 1	18 – 22	9 – 11	6 – 13
Sarepta mustard	Cruciferous	++	22 – 39	29 – 35	2 – 4	1 – 2	8 – 20	7 – 12	21 – 40	15 – 23	13 – 16	19
		00	22 – 39	29 – 35	4	2	39	1	0	40	13	19
Sunflower	Asteraceae	Normal type	36 – 55	14 – 22	5 – 6	4 – 7	14 – 20	–	–	67 – 73	–	–
Oil flax	Flax	–	42 – 52	16 – 23	4 – 6	2 – 5	15 – 25	–	–	11 – 19	50 – 68	–
Hemp	Mulberry	–	33 – 55	22 – 26	6	3	11	–	–	58	21	–
Safflower	Asteraceae	Normal type	18 – 50	12 – 18	2 – 6	1 – 4	14 – 24	–	–	63 – 79	–	–
Oilseed radish	Cruciferous	+	35 – 39	25 – 30	4 – 6	2 – 3	23 – 36	8 – 11	9 – 30	10 – 18	11 – 17	160 – 180
Oil poppy	Poppy	–	40 – 55	20 – 28	10 – 12	0 – 1	12 – 22	–	–	60 – 75	0 – 1	–
Pumpkin	Pumpkin	–	40 – 58	34 – 38	7 – 12	6 – 8	20 – 40	–	–	45 – 60	–	–
Lalemantia	Lip-flowering	–	28 – 38	26 – 29	4 – 6	1 – 3	9 – 11	1 – 2	–	60 – 70	1 – 4	–
White mustard	Cruciferous	++	24 – 34	27 – 33	2 – 4	1 – 2	15 – 36	6 – 12	24 – 57	7 – 13	9 – 11	240 – 290
		00	30 – 36	27 – 33	2 – 3	1 – 2	58 – 62	2 – 3	0 – 1	12 – 16	17 – 18	4 – 7
		+0	36 – 38	27 – 33	2 – 3	1 – 2	10 – 12	2 – 4	55 – 59	9 – 10	14 – 15	10 – 15

Variety types: ++ – with erucic acid and glucosinolates (old forms); 00 – without erucic acid and glucosinolates

Table 5.5

Chemical composition of oil of some oilseeds according to D. Shpaar (2006)

Crops	Sort type	Content oils, %	Composition of important fatty acids in oils, % of total fatty acid content: saturated fatty acids		simple unsaturated fatty acids			multiply unsaturated fatty acids		Protein content, %	Gluco-einolatse content, µmol g^{-1}
Rapeseed	++	–	3–4	1–2	12–23	9–14	41–47	15–25	10–15	–	55–75
	++	37–47	2	1	1	7	50	15	7	–	–
	00	39–48	3–5	1–2	58–62	0–1	0–1	18–22	9–11	22–25	6–13
Sarepitsa	++	–	2–3	1–2	17–34	10–12	24–40	14–18	9–11	–	70
	++	36–46	1–3	1–2	10–27	8–12	27–52	13–22	7–11	–	–
	0+	37–47	3–5	1–2	54–60	0–2	0–2	18–23	11–14	22–26	45–55
	00	–	3–4	1–2	55–57	1–2	0–2	21–23	13–14	–	< 10
Sarepta mustard	++	30–40	1–4	1–4	28–34	1–3	20–45	15–20	2–5	–	–
	++	23–39	3	1	2	7	47	16	11	29–35	–
	++	–	2–4	1–2	8–20	7–12	21–40	15–23	13–16	–	–
	00	44	4	2	39	1	0	40	13	–	19
Black mustard	++	24–38	2–4	1–2	8–19	7–12	24–43	13–23	13–16	–	55–120
White mustard	++	24–34	2–4	1–2	15–36	6–12	24–57	7–13	9–11	27–33	240–290
	00	ок.30	2–3	1–2	58–62	2–3	0–1	12–16	17–18	–	4–7
	+0	36–38	2–3	1–2	10–12	2–4	55–59	9–10	14–15	–	10–15
Radish oilseed	++	35–39	4–6	2–3	23–36	8–11	9–30	10–18	11–17	–	160–180
Crumbe	++	31–41	1–2	0,5–1	14–18	2–5	54–62	7–9	4–7	16–23	60–120

Our studies have also shown that oil radish seeds have a high fat content (on a dry matter basis) ranging from 34 to 38%, depending on the variant, and a relatively high protein content of 22.4 to 23.8%. 1 kg of dry matter of seeds contains more than 1 k.e. with a content of 170.3–185.3 g of digestible protein in each (Table). At the same time, it was noted (Maksymuk et al., 2009) that burning 1 g of rape seeds yields 26.9 J of energy, oil flax – 26.2; spring rape and camelina – 25.5; oil radish – 25.1; gray mustard – 24.3; white mustard – 22.8 J of energy.

Table 5.6

Fatty acid composition of vegetable oils, % (Kozlenko, 2011)

Acid	**Short chemical formula**	**Spring rapeseed**	**Rocket-cress**	**White mustard**	**Sarepta mustard**	**Oilseed radish**	**Camelina spring**	**Safflower**	**Oil flax**
Kaprinova	10: 0	Traces*	Traces	Traces	Traces	–	–	–	–
Laurinova	12:0	Traces	Traces	0.01	0.01	Traces	–	–	–
Miristinova	14:0	0.08	0.08	0.03	0.07	0.10	0.08	0.14	0.06
Palmitic	16:0	3.46	2.55	2.21	2.28	4.96	4.60	4.75	3.93
Palmito-oleic	16:1	0.18	0.22	0.17	0.28	0.18	0.14	0.12	0.10
Stearic	18:0	1.95	1.66	0.93	1.20	2.38	2.22	1.86	4.27
Oleic	18:1	65.70	51.21	31.84	33.22	37.43	14.99	8.74	15.36
Linoleic	18:2	19.14	20.42	8.60	8.37	15.97	17.18	82.46	12.30
Linolenic	18:3	8.44	15.77	22.08	22.53	23.92	54.00	0.85	63.30
Eicosenic	20:1	0.26	0.31	0.43	0.54	0.65	1.73	0.17	0.10
Begenic	22:0	0.33	0.28	–	0.32	0.29	1.78	0.27	0.29
Erukova	22:1	0.16	6.98	31.51	29.23	12.64	3.00	0.08	0.29
Karnaubovic	24:0	–	0.25	0.37	0.16	0.12	0.06	0.03	–
Nervonic	24:1	0.30	0.27	1.82	1.79	1.36	0.22	0.53	–
Total		100	100	100	100	100	100	100	100

* Traces – the content of this acid will be approximately less than 0.01 %.

In addition, we have determined that oil radish seeds are a potentially possible high-energy feed, 1 kg of dry matter of which provides 15.9 – 16.6 MJ of metabolizable and 26.1–27.3 MJ of gross energy.

Studies of the physicochemical properties of oil radish oil have shown that it is a semi-dry oil. During processing, the oil is well hydrated and can be successfully used in the production of margarine and soap. According to Cherepa (1952), the hydrogenation of oil radish oil resulted in salomas with a melting point of 55 °C and a titer (fatty acid pour point) of 53 °C. The saponification coefficient of the salomas is 183. The filtered product can be successfully used for soap making. Straw with a melting point of 32–36 °C can be used in unlimited quantities for margarine production. Moreover, straw from oil radish seeds was not inferior to a similar product obtained from other vegetable oils processed into margarine and soap.

Table 5.7

Experimental value of specific heat of combustion for raw materials of some oilseeds (De Andrade et al., 2012)

Crops	Maximum value of calorific value, MJ kg^{-1}				
	oil (O)	Fatty acid methyl esters (FAME)	FAME-O	Fatty acid ethyl esters (FAEE)	FAEE-FAME
Oilsed radish	39.72	40.04	0.32	–	–
Mustard	40.07	40.25	0.18	–	–
Rocket-cress	40.09	40.28	0.19	–	–
Rapeseed	39.6	39.87	0.27	40.12	0.25
Sunflower	39.46	39.71	0.25	39.80	0.09
Oil flax	39.51	40.00	0.49	39.65	-0.35

The results of the chromatographic determination of the fatty acid composition of oil radish seeds of ‘Zhuravka’ and ‘Raduga’ varieties are presented in Table 5.8.

Our results confirm the category of oil for both varieties as semi-drying for technical purposes. A high variability of fatty acid composition of oil radish seeds was noted over the years of study. Thus, for the Zhuravka variety, the content of palmitoleic acid was not detected on the chromatogram at all in 2010 and 2012.

The situation is similar with caprylic, eicosatrin and ellaidic acids. Similar features were noted for some acids for the ‘Raduga’ variety. Based on this, it was noted that the fatty acid composition of cruciferous seeds depends on weather conditions, doses of mineral fertilizers, varietal characteristics of soil nutrition, and the nature of the accumulation of acids can change towards a higher content of certain acids within close values of their molecular index. Therefore, this issue for oil radish requires additional detailed further study.

By comparing the chemical characteristics of vegetable oils for technical use with the results established for oil radish, we proved the possibility of its use for biofuel production (Tsytsiura, 2013). We have also found that oil radish at the first sowing date with a sowing rate of 2 million seeds per hectare of germinating seeds provides oil yields in the range of 0.17–0.28 t ha^{-1}, depending on the variety and level of seed yield on an unfertilized background and 0.59–0.80 t ha^{-1} on a background with $N_{60}P_{60}K_{60}$. At a sowing rate of 1.5 million units/ha of germinating seeds, these figures were 0.28–0.69 and 0.61–1.02 t ha^{-1}, respectively.

Table 5.8

Chemical composition and nutritional value of seeds of oilseed radish varieties under different fertilization (Tsytsiura and Tsytsiura, 2013)

Seeding rate, mln. units ha^{-1} of germinating seeds	Fertilizers	Content in completely dry substance, %					Dry matter, %	Content per 1 kg of dry matter			
		protein	fat	fiber.	ashes	Nitrogen-free extractives		Feed units*	Digestible protein, g	Metabolic energy, MJ	Gross energy, MJ
'Zhuravka' (average for 2010–2012)											
2,0	Without fertilizers	23.6	36.9	17.3	6.2	15.3	93.0	1.02	181.0	15.8	26.5
	$N_{60}P_{60}K_{60}$	23.9	37.8	17.1	6.5	15.6	92.7	1.01	183.7	16.1	26.9
'Raduga' (average for 2010–2012)											
2,0	Without fertilizers	22.4	37.5	17.0	5.1	16.5	93.3	1.03	170.3	15.9	26.6
	$N_{60}P_{60}K_{60}$	23.6	37.9	18.6	5.2	16.3	94.1	1.02	180.6	16.0	27.3

* – the content of feed units was adjusted for the potential nature of the food.

At the same time, the yield of biofuel from oil at the actual seed yield, according to technical standards, was 0.37–0.42 t/ha against the background of N60P60K60 application (Table 5.8).

The bioenergy evaluation of oil from oilseed radish is also highly efficient (Table 5.9).

To obtain oil from oil radish seeds, both cold and hot pressing technologies are used. The technology of cold pressing, cold pressing of vegetable oil, produces raw materials for further production of biodiesel fuel.

The oil is also used in the pharmaceutical industry. Cold pressing takes place at a temperature of at least 50 degrees Celsius. With hot pressing technology, the mass of seeds is crushed, heated and pressed at the same time. The pressed mass is divided into vegetable oil and cake. The oil content of the raw material should be at least 15%, of warehouse condition (weed-free, medium dry) (Andreeva, 2007; Oseiko, 2006; Shevchuk et al., 2011).

Table 5.9

Fatty acid composition of seeds of oil radish varieties of the first sowing term on unfertilized background, 2010–2012 (Tsytsiura, 2010)

Formula IUPAC	Fatty acids	'Zhuravka'			'Raduga'	
		2010	2011	2012	2011	2012
$C_{8:0}$	Kaprilova	–	–	0.48	–	–
$C_{11:0}$	Undekanova	0.20	0.54	0.84	–	0.19
$C_{16:0}$	Palmitic	5.62	6.04	6.09	–	5.46
$C_{16:1}$	Palmitoleic	–	0.15	–	0.13	0.14
$C_{18:0}$	Elaidinic	30.56	–	–	–	–
$C_{18:0}$	Stearic	2.03	2.19	2.38	3.41	2.38
$C_{18:1}$	Oleic	1.72	30.72	31.27	32.21	33.21
$C_{18:2}$	Linoleic	16.34	17.79	17.18	17.82	16.98
$C_{18:2}$	Linoleoylaidiene	–	1.70	2.30	2.40	–
$C_{18:3}$	Linolenic	9.63	9.26	13.17	13.57	10.28
$C_{20:0}$	Arachinic	0.79	0.09	0.79	0.85	0.11
$C_{20:1}$	Aikosenic	13.60	14.23	0.16	–	13.98
$C_{20:2}$	Eicosadienoic	0.86	0.96	10.79	11.70	0.64
$C_{20:3}$	Eicosatrinic	–	14.10	–	–	0.11
$C_{22:0}$	Begeneva	0.35	0.33	0.32	0.39	0.43
$C_{22:1}$	Erukova	16.28	0.13	12.87	15.40	14.22
$C_{22:2}$	Docosadiene	0.48	0.40	–	–	0.51
$C_{24:0}$	Lignoceric	1.52	1.21	0.42	0.54	1.37
$C_{24:1}$	Nervonova	–	0.16	1.42	1.58	–

Notes: 1. Saturated fatty acids are in italics; 2. IUPAC – International Union of Pure and Applied Chemistry.

The method of producing oil from oil radish (cold or hot pressing, extraction) is crucial in changing its biological value. During hot pressing, the raw material is heated to 105–120 ºC. During extraction, hexane or gasoline is used as a solvent, which is subsequently eliminated, but some of it still remains in the final product, absorbents and alkali are used. This production method makes the oil lighter and more transparent, and allows the use of raw materials of different quality. Experts say that heating deforms the linoleic acid molecule. Such a molecule can still serve as a fuel, but it loses its vitamin role and is unable to penetrate the delicate structures of human tissues. The difference between the two molecular structures, before and after heating the oil, is similar to that between starch and cellulose. The former can be eaten, while the latter cannot. Oil produced by hot pressing or extraction turns into a "dead" product devoid of biological value.

Table 5.10

Oil yield of oil radish varieties depending on seeding rate and fertilization at the first sowing term, t ha^{-1} (Tsytsiura, 2011)

Fertilizers	'Zhuravka' (2010–2012)				'Raduga' (2011–2012)			
	output, t ha^{-1}							
	for biological seed yield		with the actual seed harvest		for biological seed yield		with the actual seed harvest	
	oil	biofuels from oil	oil	biofuels from oil	oil	biofuels from oil	oil	biofuels from oil
	2 million units ha^{-1} of germinating seeds							
Without fertilizers	0.28	0.17	0.17	0.12	0.27	0.16	0.20	0.12
$N_{60}P_{60}K_{60}$	0.80	0.50	0.59	0.40	0.73	0.44	0.57	0.37
	1.5 million units ha^{-1} of germinating seeds							
Without fertilizers	0.69	0.41	0.39	0.23	0.42	0.25	0.28	0.17
$N_{60}P_{60}K_{60}$	1.02	0.61	0.67	0.42	0.86	0.52	0.61	0.39
$LSD_{05total}$, t ha^{-1}			0.31				0.26	

Table 5.11

Oil yield and bioenergy estimation from seeds of spring oilseeds at average levels of seed productivity (Kozlenko, 2011)

Crops	Oil content in seeds, %	Oil yield, t ha^{-1}	Caloric content of oil, MJ kg^{-1}	Energy yield with oil	
				GJ ha^{-1}	the equivalent amount of diesel fuel, l
Spring rape	43.69	1.19	39.55	47.06	1312
Barbaréa vulgáris	29.42	0.47	39.29	18.47	515
White mustard	25.55	0.66	40.56	26.77	746
Sarepta mustard	38.00	0.84	38.74	32.54	907
Oilseed radish	29.18	0.59	41.42	24.44	681
Camelina	49.73	1.14	38.22	43.57	1215
Safflower	26.55	0.50	39.7	19.85	553
Oil flax	43.57	1.02	37.52	38.27	1067

* – The calculations were made taking into account the caloric content of diesel fuel at 35.87 MJ l^{-1}.

Cold pressed oil does not require refining and deodorization (temperature 230-240°C), which destroy natural vitamins and deform essential fatty acid molecules, since during cold pressing (temperature no more than 50°C), harmful waxes and paraffins do not melt as they do during hot pressing (temperature 105-120°C) and do not pass into the oil, but remain in the cake.

In terms of ensuring efficient oil radish seed hulling and oil extraction, it is advisable to use special designs of hullers (Shevchuk et al., 2011) adapted to the physical parameters of oil radish seeds.

5.2. Evaluation of biofuels derived from oilseed radish

Fossil fuel reserves are non-renewable and finite. Several researchers report clear indications of depleting fossil fuel resources. According to estimates, the global recoverable oil reserves are diminishing at a rate of 4 billion tonnes per annum. Even if it is assumed that the depletion of these reserves continue at the present rate, it is projected that all of these reserves will be exhausted by 2060 (Saini, 2021; Saleem, 2022).

According to the forecasts of the International Energy Association (IEA), the world production of biofuels will increase by 2030 to 92–147 million tons of energy equivalent of oil. The annual growth rate of biofuel production will be 7–9%. It is expected that by 2030 the consumption of biofuels in the countries of the European Union (EU) will increase by 13–18 times compared to current indicators (Brown et al., 2020; Global biofuels…, 2022). Europe is currently the biggest consumer of bio-based diesel (i.e., biodiesel called Fatty Acid Methyl Ester or FAME and renewable diesel or HVO) in the world. This is driven by the EU's targets for renewable energy in transportation coupled with a dominant share of diesel in this sector. Both factors will continue through 2030, resulting in increased demand for bio-based diesel, from 17.9 million tonnes (20.6 billion liters) in 2020 to 22.9 million tonnes (27.1 billion liters) in 2030. In Latin America where, along Asia, the growth in consumption of diesel by 2030 is projected to be the highest in the world, demand for biodiesel will grow as well from 7.4 million tonnes (8.4 billion liters) currently to 12.7 million tonnes (14.5 billion liters) by 2030 (Global biofuels…, 2022). Urthermore, to reduce dependency on petroleum, several international agencies and governments aim to use biofuels to supply 25% of their transportation energy by 2050 (Global biofuels…, 2022; Ilić & Ödlund, 2022; Malins & Sandford, 2022). A number of biofuel national programmes have been implemented to reduce importation of fossil fuels to enhance the security of national fuel supplies. (Valdivia et al., 2016; Ramos et al., 2022).

A number of crops are grown specifically for biofuel production and are known as energy crops. Its vary according to geography: for example, corn, soybeans, willows and switchgrass are common energy crops in the United States; rapeseed, wheat, sugar beet and willows are preferentially grown in northern Europe; sugarcane is grown in Brazil; palm oil and Miscanthus giganteus are grown in Southeast Asia; and sorghum and cassava are grown in China (Anand et al., 2019; Kaletnik et.al., 2021; de Lacerda et al., 2020).

Raw materials are needed to increase the production of biofuels. The problem of shortage of raw materials will intensify as processing capacities in Europe increase. The average utilization of biodiesel production capacities introduced in the EU in recent years reaches only 75–80% (Saleem, 2022). In addition, climate change, which means a decrease in the adaptability of several wide-spread bioenergy crops, suggests a search for alternative crops with a high biofuel potential (Karmakar & Halder, 2019; Ramos et al., 2022). In the rest of the years, the replication of such crops has significantly expanded the resistance of new species and the assessment of their potential is insufficiently explored (Puricelli, 2020; Pasha et al., 2021; Torroba, 2021; Neupane et al., 2022). This especially applies to the issues of finding out the technical parameters of oil suitability for application in classic diesel engine schemes (Faria et al., 2018; Ilić & Ödlund, 2022). It was for these reasons that the aim of our research was to study oilseed radish as an agricultural crop with a high potential for oil production, which is considered as a possible component of mixed biofuels.

We will present the results of the author's research from the perspective of assessing the potential of oil radish oil as a raw material base for biofuel production (Tsytsiura, 2023). Seed of high productive 12 oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) varieties was used for investigation such as 'Alpha', 'Olga', 'Ramonta', 'Iveya', 'Fakel', 'Raiduha', 'Zhuravka', 'Snizhana', 'Nika', 'Tambovchanka', 'Lybid', 'Sabina'. The varieties were of different selection and of different ecological and geographical origin (temperate-continental, continental, moderately arid zones). The zonal technology of oilseed radish cultivation was applied: sowing date was April 8-12, sowing rate of 1.5 million germinable seeds ha^{-1}, row width 30 cm, fertilizer rate $N_{60}P_{60}K_{60}$ (pre-sowing application).

The content of moisture, ash, lipid, protein and fiber in the oilseed radish seeds were determined by the AOCS (2017) and expressed on absolutely dry weight basis.

Solvent extraction (SE) (for chromatographic analysis) (according to Zhao et al., 2017) oilseed radish seed powder was prepared by grinding portions of the seeds in a grain mill (BiOloMix N-700Y) for 25 s. The seed powder (1000 g) was subsequently soaked in 5000 mL of n-hexane for 5 h at 25 °C and filtered. The residue obtained was again extracted with 5000 mL of n-hexane. The supernatants from both steps were collected, combined and concentrated by using Rotary evaporator under vacuum at 40 °C to remove nhexane. The oil obtained was weighed and stored at 4 °C prior to analysis.

The research was conducted using the most widespread in the region, the oilseed radish variety 'Zhuravka'. Research was conducted during 2015-2020 in the certified and accredited laboratory of the quality of raw oil and fat of Vinnitsa oil seeds crushing factory (private joint stock company). All determinations were made in quadruplicate. Oil from the seeds of this variety was used for the analyses obtained by the cold pressing method. A Klarstein Olivia cold press with an internal filtration system was used. Additionally, the oil was settled for 24 hours before analysis and passed through afilter of non-woven carbon fiber material (Karbopon brand).

According to the tested and standard methods, the following oil indicators were determined: density at 20 °C (ASTM D7042-04), refractive index (ASTM D1218), oil colour and rotation of the plane of polarization at 23 °C (Paquot & Hauntfenne (1992)), specific viscosity at 20 °C (ASTM D445), kinematic viscosity of oil at 20 °C (ASTM D445), relative surface tension (ASTM D971-12), carbon residue (wt.%) (ASTM D4530), net calorific value (ASTM D240), solidification temperature (ASTM D97), flash point (ASTM D93), solubility in organic solventsdensity (ASTM F739)), acid value (ASTM D 974), content of free acids in % of oleic acid (according to the results of chromatography of the fatty acid composition), saponification value (ASTM D664), ether value (Firestone (2013)), iodine value (ASTM D5768), rhodan value (Paquot & Hauntfenne (1992)), amount of water-insoluble fatty acids (gener number Firestone (2013)), amount of unsaponifiable matter (Paquot & Hauntfenne (1992)), sulfur content (ASTM D5453)).

To evaluate the change in the physicochemical properties of the oil, it was polymerized by thermal heating at 280 °C (an Industrial 500ML High Pressure Blender Stirred Autoclave Vessel Chemical Hydrothermal Synthesis Reactor was used). Changes in the physico-chemical properties of oil during its oxypolymerization (heating of oil with oxygen purging) were also studied using the same device as during polymerization with oxygen supplied under a pressure of 1 atm when heated at two modes of 120 °C and 150 °C within half an hour. Oil without oxypolymerization was heated to a temperature of 120 °C with a duration of holding at this level of temperature for half an hour. Polymerization and oxypolymerization of oil was carried out taking into account methodical approaches in accordance with Rinaldi et al. (2017). Polymerized and oxypolymerized oil was studied according to the main physicochemical parameters during its long-term heating for 1, 2, and 3 hours on the same laboratory equipment. As a control, a polymerized oil sample without additional heating was used.

Determination of the fatty acid composition of the seed oils of mentioned above varieties was conducted out by the method of gas-liquid chromatography using chromatograph Shimadzu GC 2014 (Japan) (according to Clancy, 2013; Hübschmann, 2018) with methyl heptadecanoate standard at a concentration of 9.8 mg mL^{-1} for analysis of fatty acid composition. Samples were prepared using approximately 15 mg of product (oil), 200 µL of standard solution containing 9.8 µg of methyl heptadecanoate per 1000 µL and 1 mL of heptane (solvent). The configuration was set: SPL-2014 injector, FID-2014 flame ionization detector + TCD-2014 thermal conductivity detector. Identification of fatty acids was carried out by comparing the received chromatograms with chromatograms of such standard solutions as methyl esters of fatty acids C_6-C_{24}.

Coefficients of ER (elongation ratio, Formula 5.1), DR (desaturation ratio, Formula 5.2), ODR (oleic desaturation ratio, Formula 5.3), LDR (linoleic desaturation ratio, Formula 5.4), saturated and unsaturated fatty acid ratio (Formula 5.5) were estimated (according to Velasco et al. (1998), Pleines & Friedt, 1988). Fatty acid ratios were estimated according to Blume et al. (2018).

$$ER = \frac{(\%)C20:1 + (\%)C22:1}{(\%)C20:1 + (\%)C22:1 + (\%)C18:1 + (\%)C18:2 + (\%)C18:3} \quad (5.1)$$

where here and formulas (2-4) (%)C20:1, C22:1 – content of the corresponding fatty acid in %.

$$DR = \frac{(\%)C18:2 + (\%)C18:3}{(\%)C20:1 + (\%)C22:1 + (\%)C18:1 + (\%)C18:2 + (\%)C18:3} \quad (5.2)$$

$$ODR = \frac{(\%)C18:2 + (\%)C18:3}{(\%)C18:1 + (\%)C18:2 + (\%)C18:3}, \quad (5.3)$$

$$LDR = \frac{(\%)C18:3}{(\%)C18:2 + (\%)C18:3} \quad (5.4)$$

$$S/U = \frac{Saturated\ fatty\ acids}{Unsaturate\ d\ fatty\ acids}; \quad (5.5)$$

$$PU/MU = \frac{Polyunsatu\ rated\ fatty\ acids}{Monounsatu\ rated\ fatty\ acids}. \quad (5.6)$$

International terminology (CODEX, 2020) was used for the components of oilseed radish vegetable oil found during the analysis.

Research was carried out during 2015–2020 on the research field (arranged by coordinates N 49°11′31″, E 28°22′16″) located in the zone of the Right-bank Forest-Steppe of Ukraine. The soil cover of the research field was represented by gray forest soils with the following agrochemical parameters (for the period of crop rotation): humus 2.02–3.20%, mobile forms of nitrogen 67–92 mg kg^{-1}, phosphorus 149–220 mg kg^{-1}, potassium 92–126 mg kg^{-1} with metabolic acidity of soil solution (pHкcl) 5.5–6.0. The temperature regime and the humidification regime for the period of research for the growth of oilseed radish plants had significant differences. This allowed to analyze the influence of weather conditions on the fatty acid composition of oil in oilseed radish varieties. According to the weather conditions stress effect on the processes of seed formation of oilseed radish plants for years of observation 2015-2020 can be placed in the next decrease row 2015 (Hydrothermal coefficient ((HTC) (Formula 7.5) = 0.230–0.613) – 2017 (0.349–0.806) – 2016 (0.682–0.893) – 2020 (0.649–1.474) – 2019 (1.003–1.555) – 2018 (1.349–3.124).

$$HTC = \sum R \times (0.1 \times \sum t_{>10})^{-1}, \tag{5.7}$$

where ΣR – the amount of precipitation, mm over a period with temperatures above 10 ˚C; Σt > 10 ˚C – the sum of effective temperatures over the same period. According to Vlăduţ et al. (2018): HTC > 1.6 – excessive humidity, HTC 1.3–1.6 – humid conditions, HTC 1.0–1.3 – slightly arid conditions, HTC 0.7–1.0 – arid conditions, HTC 0.4–0.7 – very arid conditions.

The data obtained were analyzed using the analysis of ANOVA with determination of the share of influence of factors in the dispersion scheme (Wong, 2018). Tukey HSD Test in R (version R statistic i386 3.5.3) with a multiple comparisons of the parameter means the 99.9, 99 and 95% family-wise confidence level were used.

The object of research was oilseed radish (*Raphanus sativus* L. var. *oleiformis* (synonymous name *oleiferus*) Pers.) defined as a species of radish (*Raphanus sativus* L.), genus Raphanus L, subtribe II Raphanusae DC., tribe 5 Brassiceae Hayek and referred to the family Brassicaceae, order Capparidales, class Dicjtyledaneae (Francis et al., 2021). According to the results of some studies, it belongs to the group of species convar. oleiferus L., that is a group of varieties of oilseed radish with the following characteristics: plants are annual (95-110 days of vegetation), the taproot is not formed, it is grown to produce oil from the seeds and for forage purposes, vegetative and generative organs are similar to the forms of root crops (Tsytsiura, 2019). Oilseed radish has long been used as forage and green manure in Europe and South Africa. The proximate composition of seed in in tested varieties is shown in Tables 5.12–5.13.

Table 5.12

The average chemical composition of the seeds of the investigated 12 varieties of oilseed radish (content in absolutely dry matter, ± standard deviation (based on the results of the multi-year assessment 2015-2020)), (%) (Tsytsiura, 2023)

Seeds	Moisture	Protein	Lipid	Fiber	Ash
Content (%)	6.57 ± 1.17	23.6 ± 3.8	37.1 ± 3.5	17.0 ± 1.6	5.2 ± 1.1

The avarege lipid content in absolutely dry matter was 37.1 %, which is higher than among other crops. With a potential seed yield of up to 2–3.0 t ha^{-1} (Tsytsiura, 2019), the possible output of oil is 650–1000 kg ha^{-1}.

Due to results of the chromatographic analysis (Table 5.13) it was shown that seed of all varieties of oilseed radish possess a high content of oleic (18:1) (the range of values within the studied varieties 31.95–36.28%), linoleic (18:2) 15.06-16.89%, linolenic (18:3) 12.08-14.92%, gondoic (20:1) 7.89–9.26% and erucic (22:1) (14.79–17.80) fatty acids. This corresponded to the general profile of the ratio of fatty acids in cruciferous oil. The most common among listed fatty acids in the composition seed oil of Brassicaceae plants are oleic (18:1), linoleic (18:2), linolenic (18:3), gondoic (20:1) and erucic (22:1) (Ratanapariyanuch et al., 2013). The obtained results on the structure of the identified fatty acids was similar to the previously obtained results as in the recent studies of Blume et al. (2018), Fadhil et al. (2020), Stevanato & de Silva (2019), Stevanato et al. (2020), de Mello et al. (2021) and in the earlier Domingos et al., (2008), de Andrade Ávila et al. (2012), Chammoun et al. (2013), Zhao et al. (2017).

Table 5.13

Oil fatty acid composition of different oilseed radish (Raphanus sativus var. oleifera) varieties (content ± standard deviation (based on multi-year assessment 2015–2020)), (%) (Tsytsiura, 2023)

CN:DB$^{\times}$	Fatty acid / variety	'Raiduha'	'Zhuravka'	'Lybid'	'Fakel'	'Ramonta'	'Tambov-chanka'	'Alpha'	'Olga'	'Iveya'	'Sabina'	'Nika'	'Snizhana'
1	2	3	4	5	6	7	8	9	10	11	12	13	14
C 8:0 $^{\times\times}$<2e-3*	Octanoic $^{\times\times\times}$ (26.8)	0.16 ± 0.05	0.36 ± 0.08	0.21 ± 0.09	0.11 ± 0.05	0.00 (trace)	0.00	0.00	0.00	0.00 *(trace)	0.00	0.00	0.00 (trace)
C 11:0 *<2e-3**	Undecanoic (32.4)	0.33 ± 0.07	0.55 ± 0.11	0.18 ± 0.05	0.14 ± 0.04	0.11 ± 0.07	0.15 ± 0.06	0.00	0.00	0.00 (trace)	0.00	0.00	0.00 (trace)
C 14:0 *<2e-1^{ns}*	Myristoleic (22.8)	0.07 ± 0.04	0.07± 0.04	0.08 ± 0.03	0.06 ± 0.05	0.04 ± 0.03	0.06 ± 0.02	0.06 ± 0.02	0.07 ± 0.01	0.04 ± 0.02	0.04 ± 0.01	0.05 ± 0.01	0.03 ± 0.01
C 16:0 *<2e-4**	Palmitic (18.5)	5.11 ± 0.78	4.68 ± 0.89	5.06 ± 1.11	5.00 ± 1.23	5.02 ± 1.17	5.08 ± 1.09	5.33 ± 0.87	5.22 ± 0.85	5.12 ± 1.26	4.84 ± 1.41	4.76 ± 0.59	5.02 ± 0.64
C 16:1 *<2e-1^{ns}*	Palmitoleic (23.3)	0.13 ± 0.03	0.14 ± 0.05	0.15 ± 0.04	0.15 ± 0.03	0.11 ± 0.04	0.08 ± 0.02	0.12 ± 0.03	0.10 ± 0.02	0.07 ± 0.02	0.09 ± 0.01	0.10 ± 0.05	0.12 ± 0.02
C 18:0 *<2e-3**	Stearic (16.9)	2.60 ± 0.33	2.37 ± 0.51	2.46 ± 0.30	2.03 ± 0.44	2.12 ± 0.29	2.21 ± 0.39	2.24 ± 0.67	2.29 ± 0.55	2.26 ± 0.51	2.13 ± 0.41	2.11 ± 0.67	2.13 ± 0.59
C 18:1 *<2e-3**	Elaidic (17.1)	0.08 ± 0.02	0.18 ± 0.05	0.05 ± 0.01	0.11 ± 0.02	0.14 ± 0.01	0.07 ± 0.02	0.00	0.00 (trace)	0.00	0.00	0.00 (trace)	0.00
C 18:1 *<2e-3**	[cis -9] Oleic (14.2)	33.53 ± 4.38	33.19± 3.89	34.08 ± 3.55	31.95 ±5.14	31.34 ±4.89	33.72 ± 5.17	35.91 ± 4.87	33.59 ± 6.17	33.27 ± 5.91	34.97 ± 5.17	34.62 ± 4.14	36.28 ± 4.96
C 18:2 *<2e-6***	[cis -9,12] Linoleic (20.8)	15.22 ± 3.56	15.53 ± 3.25	15.06 ± 3.24	16.81 ± 3.51	15.70 ± 4.11	17.08 ± 4.09	16.19 ± 3.77	16.90 ± 3.52	16.61 ± 3.78	16.89 ± 4.05	16.12 ± 4.26	16.23 ± 3.77
C 18:3 *<2e-6***	[cis-9, 12, 15] α-Linolenic (18.5)	12.40 ± 2.21	12.08 ± 2.39	13.01 ± 2.49	13.10 ± 2.56	13.28 ± 2.93	12.26 ± 2.54	13.66 ± 2.49	13.84 ± 2.72	14.92 ± 2.84	14.42 ± 2.41	14.03 ± 1.98	12.97 ± 1.95
C 20:0 *<2e-6***	Arachidic (27.9)	0.96 ± 0.17	0.91 ± 0.11	0.94 ± 0.14	0.66 ± 0.10	0.76 ± 0.20	0.79 ± 0.27	0.70 ± 0.31	0.72 ± 0.19	0.71 ± 0.23	0.75 ± 0.29	0.71 ± 0.34	0.63 ± 0.31
C 20:1 *<2e-6***	Gondoic (22.7)	9.15 ± 2.07	8.48 ± 2.05	8.84 ± 2.03	9.12 ± 1.99	8.92 ± 1.84	8.55 ± 1.77	8.12 ± 1.71	8.06 ± 1.92	7.92 ± 1.87	7.89 ± 2.19	9.14 ± 2.29	9.26 ± 1.67
C 20:2 *<2e-5***	[cis -11, 14] Eicosadienoic(32.6)	0.47 ± 0.14	0.39 ± 0.17	0.26 ± 0.14	0.28 ± 0.12	0.40 ± 0.15	0.28 ± 0.10	0.33 ± 0.09	0.41 ± 0.11	0.21 ± 0.08	0.32 ± 0.11	0.20 ± 0.14	0.24 ± 0.09

(End of Table 5.13)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
C 20:3 *<2e-3***	Eicosatrienoic (25.2)	0.13 ± 0.06	0.12 ± 0.04	0.10 ± 0.02	0.10 ± 0.03	0.12 ± 0.03	0.08 ± 0.02	0.15 ± 0.03	0.13 ± 0.03	0.08 ± 0.03	0.07 ± 0.03	0.05 ± 0.01	0.08 ± 0.03
C 20:4 *<2e-3***	Arachidonic (24.5)	0.12 ± 0.03	0.14 ± 0.02	0.14 ± 0.03	0.12 ± 0.04	0.13 ± 0.05	0.15 ± 0.02	0.10 ± 0.03	0.11 ± 0.03	0.10 ± 0.04	0.05 ± 0.01	0.05 ± 0.02	0.07 ± 0.02
C 20:5 *<2e-7****	[cis -5, 8, 11, 14, 17] Eicosapen-taenoic (21.7)	1.24 ± 0.27	1.11 ± 0.22	1.08 ± 0.31	1.02 ± 0.24	1.37 ± 0.29	0.97 ± 0.23	0.00	0.00	0.00	0.00	0.00 (trace)	0.00 (trace)
C 21:0 *<2e-4***	Geneicosanoic (28.3)	0.00 (trace)	0.46 ± 0.09	0.00 (trace)	0.00 (trace)	0.00	0.36 ± 0.07	0.00	0.44 ± 0.13	0.39 ± 0.10	0.32 ± 0.12	0.00 (trace)	0.33 ± 0.09
C 22:0 *<2e-7****	Behenic (29.8)	0.37 ± 0.11	0.41 ± 0.07	0.39 ± 0.14	0.08 ± 0.03	0.28 ± 0.10	0.07 ± 0.02	0.32 ± 0.12	0.24 ± 0.09	0.30 ± 0.12	0.00 (trace)	0.31 ± 0.07	0.00 (trace)
C 22:1 *<2e-7****	[cis -13] Erucic (17.9)	15.20 ± 2.07	15.95 ± 2.18	15.93 ± 2.79	16.70 ± 2.56	17.80 ± 2.75	15.59 ± 2.92	17.66 ± 3.02	15.74 ± 3.09	16.18 ± 2.93	15.73 ± 2.38	16.30 ± 2.49	14.79 ± 2.37
C 22:2 *<2e-6****	[cis -13, 16] Docosadienoic (26.7)	0.38 ± 0.09	0.51 ± 0.12	0.25 ± 0.09	0.27 ± 0.08	0.15 ± 0.04	0.17 ± 0.05	0.12 ± 0.03	0.14 ± 0.04	0.17 ± 0.04	0.11 ± 0.05	0.10 ± 0.03	0.12 ± 0.04
C 23:0 *<2e-4***	Tricosanoic (27.5)	0.45 ± 0.14	0.42 ± 0.12	0.41 ± 0.09	0.39 ± 0.17	0.42 ± 0.11	0.42 ± 0.08	0.47 ± 0.09	0.44 ± 0.07	0.46 ± 0.08	0.43 ± 0.12	0.39 ± 0.08	0.46 ± 0.17
C 24:0 *<2e-4***	Lignoceric (28.1)	0.44 ± 0.24	0.52 ± 0.27	0.31 ± 0.11	0.39 ± 0.18	0.57 ± 0.17	0.14 ± 0.05	0.34 ± 0.16	0.34 ± 0.14	0.45 ± 0.09	0.33 ± 0.11	0.38 ± 0.14	0.41 ± 0.24
C 24:1 *<2e-10******	Nervonic (34.9)	1.46 ± 0.36	1.43 ± 0.34	1.01 ± 0.28	1.41 ± 0.50	1.22 ± 0.42	1.72 ± 0.48	1.18 ± 0.51	1.22 ± 0.39	0.74 ± 0.30	0.62 ± 0.28	0.58 ± 0.24	0.83 ± 0.33
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total saturated		11.34	11.65	10.55	9.41	9.87	9.73	9.91	10.31	10.11	9.27	9.01	9.37
Monounsaturated		59.55	59.37	60.06	59.44	59.53	59.73	59.99	58.71	58.18	59.30	60.74	61.28
Polyunsaturated		29.11	28.98	29.39	31.15	30.60	30.54	30.10	30.98	31.71	31.43	30.25	29.35
Total unsaturated		88.66	88.35	89.45	90.59	90.13	90.27	90.09	89.69	89.89	90.73	90.99	90.63
ER		0.285	0.286	0.285	0.294	0.306	0.277	0.257	0.270	0.271	0.263	0.282	0.269
DR		0.323	0.323	0.323	0.341	0.332	0.336	0.337	0.349	0.355	0.348	0.334	0.326
ODR		0.451	0.453	0.451	0.483	0.479	0.465	0.454	0.478	0.487	0.472	0.465	0.446
LDR		0.449	0.438	0.463	0.438	0.458	0.418	0.458	0.450	0.473	0.461	0.465	0.444
S/U		0.128	0.132	0.118	0.104	0.110	0.108	0.110	0.115	0.112	0.102	0.099	0.103
PU/MU		0.489	0.488	0.489	0.524	0.514	0.511	0.502	0.528	0.545	0.530	0.498	0.479

*trace – the concentration was less 0.01%; $^{\times}$– Carbon number (CN) per double bond (DB); $^{\times\times}$ – level Pr(>F) for a given fatty acid to compare between oilseed varieties (Tukey HSD Test results, signifscant codes: '***' 0.001 '**' 0.01 '*' 0.05 'ns' nonsignificant); $^{\times\times\times}$ – the average share of the influence of hydrothermal conditions of vegetation (%) on the amount of fatt acid content in the two-factor ANOVA system (A – year conditions, B – variety with an assessment of the content of the corresponding fatty acid).

The obtained structure of the fatty acid composition is closest to the results of Blume et al. (2018) and Domingos et al. (2008). However, the obtained data give reason to note a number of features that was different from the results obtained in the specified studies. In particular, the significance of the differences in the concentration of fatty acids within the varieties of different ecological and geographical origin in the presence of a wider spectrum of cis-isomers of fatty acids was established. According to Singer et al. (2016) this type of formation of the structure of fatty acids indicated the high-amplitude nature of temperature and moisture during the period of seed formation and filling. At the same time, the difference is proven statistically. The level of significance for the majority of fatty acids (linoleic, α-linolenic, arachidic, gondoic, eicosadienoic, eicosapentaenoic, behenic, erucic, docosadienoic) in the comparison of oilseed radish varieties is $p<0.01$. For nervonic fatty acid, this level was $p <0.001$, and for myristoleic and palmitoleic fatty acids, the differences in the content of varieties were insignificant. For the rest of the fatty acids, the significance of differences between varieties was $p<0.05$. Among the full list of the identified composition, no such acid as octanoic (8:0) was detected in 5 varieties, in 4 varieties such acids as undecanoic (11:0), elaidic (18:1) and eicosapentaenoic (20:5) were found in two varieties of fatty geneicosanoic acid (21:0). At the same time, these same acids were not identified for oil radish in the same studies by Blume et al. (2018) and Domingos et al. (2008). Such results allow us to ascertain a wider range of fatty acids in the composition of oilseed radish than was noted and to form a classification of varieties according to the suitability of its oil for biofuel use.

The variability of the values of the concentration of the corresponding fatty acids by the value of the presented standard deviation was ranked for varieties in the range from 7.6 to 53.7%. Variability was due to both annual variance and internal variability within the limits of the obtained results of four-fold repetition of determinations, taking into account the general error of the experiment. The level of variation was consistent with the generalization results of Velasco et al. (1998), Mendal et al. (2002), de Andrade Ávila et al. (2012), Wendlinger et al. (2014). It should be noted that according to the amino acid composition of other cruciferous crops (statistical long-term data according to Giakoumis (2018)), in terms of dominant fatty acids, oil of oilseed radish contains (as a percentage of comparison with the concentration) myristoleic fatty acid by 25% more than in rapeseed, spring bittercress, camelina and red by 42.9% more than in white mustard. The content of oleic fatty acid is 43.0% lower than that of rapeseed and 26.9% lower than that of spring bittercress, but 17.6% higher than that of white mustard and 1.5 times higher than that of camelina. In terms of erucic acid content in radish oil was second only to white mustard (40.1% reduction). The content of linoleic fatty acid is less than 7.3% in comparison with camelina and 16.6% and 21.8%, respectively, less in rapeseed and spring bittercress, and greater by 14.3% less than in white mustard. The content of linolenic fatty acid is 1.8 times more than that of rapeseed and 50.0% more than that of spring bittercress, but on the same level with white mustard and 55.7% less than camelina.

In addition, the share of the influence of hydrothermal conditions of the vegetation of oilseed radish on the structure of the fatty acid composition of its oil was determined in the dispersion scheme of year-variety-relevant fatty acid-random (not account) factors. The influence value thus obtained ranged from 16.9% for stearic fatty acid to 34.9% for nervonic fatty acid. The determined nature of the effect allows to evaluate the components of the fatty acid composition of the oil for plasticity and stability and in the future to predict the approximate fatty acid composition of the oil of this variety based on its genotypically characteristic structure and weather conditions during the period of seed formation.

According to the chemical structure of the fatty acid composition, the ratio of saturated and unsaturated fatty acids in all studied varieties had a small interval ratio of 9.01–11.65:88.35–90.99 (%). Among the unsaturated fatty acids, monounsaturated fatty acids prevailed with the average value for varieties according to their ratio to polyunsaturated as 59.69:30.34 (%) with an average share of saturated 9.97%. The established differences in the fatty acid composition led to a corresponding spread of values according to the main fatty acid ratios (Formulas 5.1–5.6). Thus, Blume et al. (2018) indicate that very large amount of polyunsaturated fatty acids will significantly reduce oxidative stability of obtained fuel and oil presents a mixture had a large number of different fatty acids. For this reason, some coefficients are usefull for more accurate assessment of the qualitative composition of different oil types: ER (elongation ratio), DR (desaturation ratio), ODR (oleic desaturation ratio), LDR (linoleic desaturation ratio). Mentioned ratios show relation between different groups of fatty acids with similar properties and probably could show activity of respective desaturase or elongase (Atabani et al., 2013). It is indicated (Blume et al. (2018)) that biodiesel fuel could be divided into two groups: heavy and light (which could be used as additive to aviation fuel) type of fuel according to length of carbon chain. The biggest difficulty of fatty acid composition assessment is large number of various fatty acids, each of which has specific properties. Obtained fuel from certain types of oil should have small carbon number (preferably not more than 18), therefore important is the contents of the mono- and polyunsaturated fatty acids with short chain (such as C 18:2, C 18:3). On the other hand very large amount of polyunsaturated fatty acids will significantly reduce oxidative stability of obtained fuel (Firestone, 2013). Also to assess the results of the chromatographic analysis used as indicators S/U (saturated fatty acids/unsaturated fatty acids) and PU/MU (polyunsaturated fatty acids/monounsaturated fatty acids) proportions (Blume et al., 2018). At the same time, in the practice of evaluating oils for biofuel (Clancy, 2013; Shah et al., 2013; Faria et al., 2018), preference should be given to oils with a high content of unsaturated fatty acids (primarily monounsaturated) and also the lowest value such fatty acid ratios PU/MU, ER DR. The highest index of LDR value has been found due to the highest content of linolenic acid (C18:3) what could indicate reduced oxidative stability (Blume et al., 2018).

According to the indicated dataset and considering as the resulting indicator PU/MU (Fadhil et al., 2020), the investigated varieties of oilseed radish can be placed in the following order of increasing suitability of its oil as a biofuel component: ‘Zhuravka’ – ‘Raiduha’ – ‘Lybid’ – ‘Olga’ –’Iveya’ – ‘Ramonta’ – ‘Alpha’ – ‘Tambovchanka’ – ‘Fakel’ – ‘Snizhana’ – ‘Sabina’ – ‘Nika’. It should also be noted that the high content of erucic fatty acid 14.80-17.80% allowed to classify this oil as not suitable for food purposes and determined the importance of its application for bioenergetic. The results of the oil fatty acid composition were confirmed by the clustering (Figure 5.3).

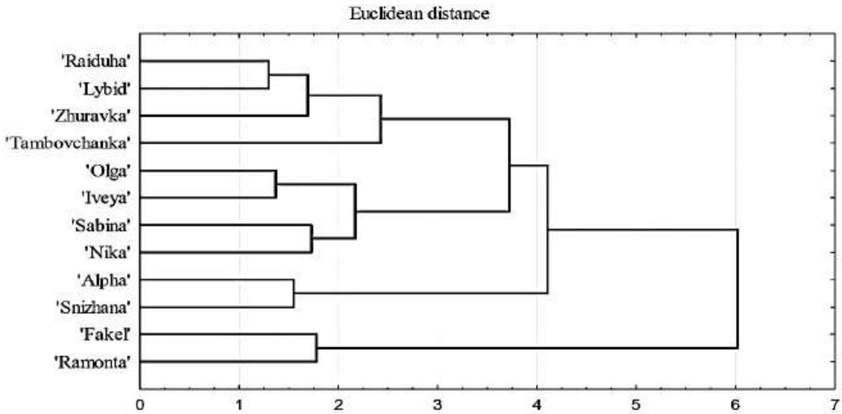


Figure 5.3 – Cluster analysis of 12 oilseed radish varieties by fatty acid content in its oil (full linkage method for the 2015-2020 dataset) (Tsytsiura, 2023)

This cluster confirmed the significance of the difference between the studied varieties in the concentration of individual fatty acids according to the seven groups of Euclidean distances determined in the clustering of data according to the full linkage method scheme. It also indicated the proximity of varieties were in neighboring positions in a certain range of suitability of its oil for biofuel use. That was confirmed the reliability of the conducted ranking of varieties.

It is noted (Mat et al., 2020) the importance, together with the study of the fatty acid composition of the oil, of the assessment of its physical and physicochemical constants. The data of such assessment are presented in Table 3. The values of the presented groups of indicators correspond to the defined interval indicators for oil in the species category ‘Fodder radish crude oil’ (CERBIO, 2007; de Andrade Ávila, 2013; Clancy, 2013; Ratanapariyanuch et al., 2013; Faria et al., 2018). According to the specified parameters, the oil from oilseed radish varieties under ordinary cold pressing belongs to the group of semi-drying oils. In comparison to a number of vegetable oils (the first 7 was most widely used in biofuel practice in the research region, and jatropha oil is gaining popularity (Riayatsyah et al., 2022)), oil from oil radish should be classified as suitable for biofuel use by basic parameters. This is confirmed by both the comparison and the conclusions of a number of studies (de Andrade Ávila, 2013; Clancy, 2013; Blume et al., 2018; Fadhil et al., 2020; Paricaud et al., 2020). The positive aspects of this oil include a high calorific value of combustion (one of the highest among cruciferous oils), a relatively low percentage of carbon residue, which is 0.07-0.20% lower than that of traditional rapeseed and soybean oils. The last factor was positive in view of the predicted using of fuel equipment. The negative aspects included high acidity and lower values of the 'solidification temperature' indicator against the background of a significantly higher value of the flash point (265 °C). The interaction of these factors in view of the research of Giakoumis (2018) and Paricaud et al. (2020) limits its use in a single-component version even with the addition of corrective organic additives (Domingos et al., 2008). According to the presented data, it is expedient to use this oil in the variant of combined use of mixed biofuels. At the same time, the optimal version of the mixtures should be investigated in detail, despite a certain reciped recommendation in practice with the participation of oilseed radish oil (Pedro et al., 2009; de Andrade Ávila et al., 2012; Clancy, 2013; Faria et al., 2018; Fadhil et al., 2019). This was confirmed by the results of changes in the basic physical and physicochemical parameters of radish oil during the polymerization and oxypolymerization process (Tables 5.14–5.15). Due to the polymerization of the oil at a temperature of 280 °C, which corresponded to the maximum possible level of the flash point of the oil and its heating in combination with oxypolymerization, it was possible to study changes in the physical and physico-chemical parameters of the oil under conditions close to the conditions in the fuel supply system and its preparation before injection into the combustion chamber of the engine.

Considering the results of research by Dahmen & Marquardt (2017), Tucki et al. (2019) the behavior of oil from oil radish under the combination of oxypolymerization and constant heating modes can be assessed as stable. Both modes of oxypolymerization at temperatures of 120°C and 150°C showed similar changes in the specific gravity of the oil. Moreover, long-term heating increased this indicator to control ($p<0.05$) only in the option of heating for 2 and 3 hours. The absence of the previous oxypolymerization process increased the reaction sensitivity of the oil to long-term heating during the polymerization process, which led to a significant ($p<0.05$)

indicator of the specific density of the oil already in the option of heating for one hour.

On the contrary, the refractive index had more significant changes in the heating variants of pre-oxypolymerized oil. Oxypolymerization was also positively reflected on the basic indicators of acid, iodine, ether numbers and saponification number. Significant changes in the full set of these parameters ($p<0.05...0.01$) were noted only in the variant of preliminary oxypolymerization at 150 °C with heating for 2 and 3 hours. The oil without prior oxypolymerization had more significant changes ($p<0.01...0.001$) in terms of the basic indicators of the physicochemical properties of the oil compared to the control, especially in the heating option for 3 hours.

The obtained results confirmed the suitability of oil from oilseed radish for thermodynamic combustion processes in regulated pressure and temperature systems. Such results are consistent with the data of Chammoun (2013), Ratanapariyanuch (2013) and Faria et al. (2018).

However, these conclusions are based not only on the analysis of the chemical composition of the oil itself, but also take into account certain transformation processes that the oil undergoes during its stay in the fuel system of a heated engine.

Based on the comparison of the oil from the seeds of oilseed radish varieties of different breeding both in terms of the structure of the fatty acid composition and its physical and physico-chemical properties, this crop should be considered as one of the promising ones for use in the production of multicomponent biofuels. Oil from these varieties on average is characterized by high content of monounsaturated (59.69%) fatty acids, especially the highest value of oleic (18:1) acid (33.87%).

Polyunsaturated/monounsaturated fatty acid ratio (PU/MU) was rather lower – 0.479–0.545, so oxidative stability of this oil was high. The other fatty acid ratios (desaturation ratio (DR) – 0.326–0.349, elongation ratio (ER) – 0.257–0.306, oleic desaturation ratio (ODR) – 0.446–0.487, linoleic desaturation ratio (LDR) – 0.418–0.473, saturated/unsaturated (S/U) – 0.099–0.132) indicate a wide range of potential biofuel use of the oil of this plant species. Particularly valuable in this regard was the varieties of 'Sabina' and 'Nika' with the highest value of oleic (18:1) acid (34.62–34.97%) with an S/U ratio of 0.099–0.102.

Table 5.14

Average values of physical and physicochemical indicators of oil for 12 varieties of oilseed radish (*Raphanus sativus* var. *oleifera*) (± standard deviation (2015–2020)) and the range of its values for oils of other crops (Tsytsiura, 2023)

Sample of oil	**Organoleptic properties**				
	colour (Lovibond, 1 in.)	**transparency**	**colour (iodine scale)**	**odor**	**taste**
Cold pressed oil	Y25.00, R2.00 – Y35.00, R2.60	absolute transparency after 24 hours	30-40	light radish hue	soft, satisfying with a radish taste

Sample of oil	Physical indicators										
	density at 20 °C, kg m^{-3}	refractive index at 20 °C,	rotation of the plane of polarization at 23 °C, °	specific viscosity at 20 °C, $mm^2 s^{-1}$	kinematic viscosity of oil at 20°C $mm^2 s^{-1}$	relative surface tension	carbon residue (wt.%)	net calorific value, MJ kg^{-1}	solidification temperature,°C	flash point, °C	solubility in organic solventsdensity
Cold pressed oil	0.912 ± 0.047	1.468 ± 0.012	-0.73 ± 0.02	70.39 ± 0.58	77.18 ± 0.55	0.459 ± 0.011	0.31 ± 0.12	37.93 ± 0.29	-11.5 ± 2.0	265.0 ± 23.7	Well soluble

Sample of oil	Chemical indicators								
	acid value, mg KOH g^{-1}	content of free acids in % of oleic acid	saponification value, mg KOH g^{-1}	ether value, mg KOH g^{-1}	iodine value, g I_2 $(100·g)^{-1}$	rhodan value, g $(SCN)_2$ $(100·g)^{-1}$	amount of water-insoluble fatty acids (gener number)	amount of unsaponifiable matter, %	sulfur content (wt.%)
Cold pressed oil	3.80 ± 0.30	0.45 ± 0.10	170.0 ± 1.8	168.4 ± 2.1	104.8 ± 2.4	81.4 ± 1.5	92.2 ± 1.8	1.17 ± 0.15	0.0017 ± 0.005

(End of Table 5.14)

Range of observed values of indicators in various studies for the period 1950–2018 based on Firestone (2013), Tsytsiura & Tsytsiura (2015), Giakoumis (2018)	Rapeseed (*Brassica napus* subsp. Napus)	White mustard (*Sinapis alba* L)	Spring bittercress (*Brassica campestris* var. *oleifera* f *annua* D.C)	Camelina (*Camelina sativa* (L.) Crantz)	Safflower (*Carthamus tinctorius* L)	Soybean (*Glycine max* (L) Merrill)	Linseed (*Linum usitatissimum* L. var. *intermedia*)	Jatropha (*Jatropha curcas* L.)
Kinematic viscosity of oil at 20°C, mm^2 s^{-1}/	74.6–77.2	66.6–69.7	75.8–78.4	51.2–53.4	65.8–68.4	56.9–57.8	60.8–62.9	57.8–61.3
Acid value	0.1–11.0	0.06–8.5	0.8–7.3	0.5–5.0	0.8–5.8	0.0–5.7	0.5–1.5	8.7–9.8
Iodine value	95–118	79–115	105–122	133–155	138–155	120–141	175–204	98–103
Flash point, °C	255.4–276.1	238.7–257.2	245.9–264.7	183.7–218.5	246.9–277.3	230.7–254.4	220.4–249.8	232.8–247.5
Solidification temperature,°C	0.0…–10.0	–8.0…–16.0	–6.0…–8.0	–14.0…–16.0	–8.0…–16.0	–10.0…–18.0	–16.0...–27.0	0.5…1.0
Carbon residue (wt.%)	0.38–0.51	0.33–0.46	0.39–0.55	0.24–0.32	0.42–0.67	0.44–0.69	0.27–0.41	0.47–0.72
Net calorific value, MJ kg^{-1}	37.1–40.2	36.4–38.2	36.8–37.2	36.5–37.0	36.4–37.0	37.0–37.6	36.7–37.0	36.7–37.2

Table 5.15

Changes in the physicochemical parameters of oxypolymerized and unoxypolymerized oil of 'Zhuravka' variety in the process of its temperature polymerization (heating at 280 °C (average value for 4 years of study 2017–2020 (± standard deviation)) (Tsytsiura, 2023)

Variant	Heating, hours	Density at 20 °C, kg m^{-3}	Refractive index	Acid value	Content of free acids in % of oleic acid	Saponification value	Ether n value	Iodine value
Control variant (heated oil)	-	0.913 ± 0.058	1.471 ± 0.001	3.75 ± 0.50	2.10 ± 0.55	181.15 ± 2.84	175.52 ± 7.35	108.52 ± 2.33
Heated oil without oxypolymerization up to 120°C	1	0.928^{c*} ± 0.041	1.472^{ns} ± 0.002	18.30^{a} ± 1.35	9.05^{a} ± 2.15	186.08^{c} ± 3.52	170.43^{c} ± 6.51	93.09^{b} ± 3.45
	2	0.931^{c} ± 0.044	1.473^{c} ± 0.003	25.10^{a} ± 1.52	12.55^{a} ± 2.30	189.42^{c} ± 3.85	167.55^{b} ± 5.44	82.82^{a} ± 2.64
	3	0.935^{b} ± 0.051	1.474^{c} ± 0.002	27.95^{a} ± 1.60	14.20^{a} ± 2.70	188.21^{c} ± 2.15	157.71^{a} ± 3.62	71.72^{a} ± 3.52
Oxypolymerized oil at temperature 120 °C	1	0.917^{ns} ± 0.035	1.473^{c} ± 0.002	3.50^{c} ± 1.78	1.74^{c} ± 0.16	177.89^{ns} ± 1.53	175.22^{ns} ± 4.10	105.85^{ns} ± 2.83
	2	0.924^{c} ± 0.041	1.474^{c} ± 0.002	3.65^{ns} ± 1.92	1.82^{c} ± 0.18	180.05^{ns} ± 3.20	175.59^{ns} ± 4.52	97.83^{b} ± 3.15
	3	0.924^{c} ± 0.052	1.474^{c} ± 0.002	3.79^{c} ± 1.87	1.87^{c} ± 0.14	181.55^{ns} ± 2.58	176.89^{ns} ± 3.57	97.47^{b} ± 2.81
Oxypolymerized oil at temperature 150 °C	1	0.914^{ns} ± 0.036	1.473^{c} ± 0.002	3.40^{c} ± 1.72	1.75^{c} ± 0.21	179.14^{ns} ± 3.05	174.85^{ns} ± 3.89	103.92^{c} ± 3.92
	2	0.920^{c} ± 0.053	1.473^{c} ± 0.003	3.48^{c} ± 1.88	1.72^{c} ± 0.28	181.53^{ns} ± 3.28	178.15^{c} ± 4.18	92.56^{b} ± 4.09
	3	0.927^{c} ± 0.067	1.475^{b} ± 0.004	3.59^{c} ± 1.97	1.74^{c} ± 0.37	183.12^{ns} ± 3.91	179.58^{c} ± 4.63	91.72^{b} ± 4.56
level *Pr(>F)* for the Tukey HSD Test		*<2e-3*[*]	*<2e-2*[*]	*<2e-3*[*]	*<2e-6*[**]	≈ ns	*<2e-2*[*]	<2e-7[**]

[*]–letter indexing for the appropriate confidence level (in comparison to the control variant): a'***' 0.001; b'**' 0.01; c '*' 0.05; ns (nonsignificant).

The possibility of successful use of oil from oilseed radish is also confirmed on the basis of a comparative analysis of its basic properties with other oils common in biofuel production. Among the valuable features, a low level of carbon residue (0.31 wt.%) and low sulfur content (0.0017 wt.%), a high level of calorific value (37.93 MJ kg^{-1}), preservation of the main physical and physico-chemical parameters of the oil during high-temperature flow (polymerization) especially against the background of its oxypolymerization. The last factor confirms the possibility of successful use of this oil in closed engine systems. However, low freezing point and high flash point, higher values of its viscosity give reasons to recommend its use in the format as a component of mixed biofuels. This direction needs additional scientific study.

The results of such studies, including chromatographic analysis of radish oil for composition and content of higher fatty acids (HFAs) are shown in Table 5.16.

Table 5.16

Content and composition of higher fatty acids of radish oil (Ukhanov, 2018)

Fatty acid	Formula	Content in radish oil, %
1	2	3
Saturated, including:		9.372
Myristic	$C_4H_{28}O_2$	0.046
Pentadecane	$C_{15}H_{30}O_2$	0.018
Palmitic	$C_{16}H_{32}O_2$	5.107
Stearic	$C_{18}H_{36}O_2$	2.458
Arachinic	$C_{20}H_{40}O_2$	0.893
Behenic	$C_{22}H_{44}O_2$	0.403
Lignoceric	$C_{24}H_{48}O_2$	0.511
Monounsaturated, including:		55,159
Palmitooleic	$C_{16}H_{30}O_2$	0.114
Oleic	$C_{18}H_{34}O_2$	32.194
Gondoic	$C_{20}H_{38}O_2$	9.155
Erucic	$C_{22}H_{42}O_2$	12.517
Nervonic	$C_{24}H_{46}O_2$	1.179
Polyunsaturated, including:		35,408
Linoleic	$C_{18}H_{32}O_2$	22.015
Eicosadiene	$C_{20}H_{36}O_2$	0.424

(End of Table 5.16)

1	2	3
Docosadiene	$C_{22}H_{40}O_2$	0.024
u-linolenic	$C_{18}H_{30}O_2$	-
a-linolenic	$C_{18}H_{30}O_2$	12.800
Docosatrienoic	$C_{22}H_{38}O_2$	0.030
Stearidonic	$C_{18}H_{28}O_2$	-
Arachidonic	$C_{20}H_{32}O_2$	0.115

The total content of monounsaturated HFAs was 55.2%, polyunsaturated 35.4%, and saturated acids 9.4%.

The content of erucic acid 12.5%, oleic acid 32.2%, linoleic acid 22% and a-linolenic acid 12.8% were high in radish oil.

Evaluation of the effect of commercial mineral diesel fuel additive on the ratio of higher fatty acids in blended radish-mineral fuels

Blended fuel with different content of commercial mineral diesel fuel in the radish oil on the ratio of higher fatty acids (HFA) was investigated to determine the extent of the effect of addition of commercial mineral diesel fuel to radish oil on the ratio of higher fatty acids (HFA). The addition of mineral diesel fuel to the cutting oil resulted in a slight change in the ratio of HFAs in the vegetable oil (Table 5.17).

Table 5.17

Effect of commercial mineral diesel fuel additive on the relative content of HFCs in radish oil and blended radish-mineral fuel (Ukhanov, 2018)

Fatty acid	**Relative content,%**					**LSD_{05}**
	Share of oil in the mixture, %					
	100	**90**	**75**	**50**	**25**	
1	2	3	4	5	6	7
Myristic	0.046	0.034	0.028	0.022	0.021	0.004
Pentadecane	0.018	0.144	0.332	0.985	1.975	0.017
Palmitic	5.107	5.088	5.068	5.078	5.085	0.054
Palmitooleic	0.114	0.131	0.145	0.193	0.265	0.017
Stearic	2.458	2.381	2.403	2.290	2.189	0.032
Oleic	32.194	32.144	32.040	31.005	31.226	0.222
Linoleic	22.015	21.937	21.935	22.201	21.420	0.134

(End of Table 5.17)

1	2	3	4	5	6	7
Y-linolenic	-	-	0.009	0.022	0.022	0.003
a-linolenic	12.800	12.888	12.775	12.915	12.410	0.148
Arachinoic	0.893	0.902	0.905	0.914	0.885	0.014
Gondoic	9.155	9.016	9.091	8.928	8.866	0.203
Eicosadiene	0.424	0.454	0.473	0.610	0.628	0.031
Arachidonic	0.115	0.124	0.113	0.147	0.120	0.006
Behenoic	0.403	0.408	0.421	0.462	0.503	0.012
Erucic	12.517	12.546	12.512	12.435	12.560	0.154
Docosadiene	0.024	0.022	0.014	0.008	0.081	0.009
Docosatrienoic	0.030	0.026	0.027	0.022	0.031	0.009
Lignoceric	0.511	0.527	0.481	0.542	0.481	0.023
Nervonic	1.179	1.234	1.232	1.225	1.238	0.026

Significant increase in the content of pentadecanoic, palmy-toleic and behenic acids was observed when radish oil was mixed with commercial mineral fuel. A significant decrease in the content of linoleic, gondoic and arachinic acids was also noted.

In addition, it was noted that with increasing the proportion of mineral fuel in DCT, a decrease in the total content of HFAs with 14, 15 and 18 carbon atoms in the chain and an increase in the total content of HFAs with 22 and 24 carbon atoms in the chain was observed.

Vegetable oil obtained from radish is a mixture of mono-, di- and triacylglycerols containing higher aliphatic acids, i.e. high molecular weight acid-containing compounds with a hydrocarbon base linked to the glycerol molecule.

To determine the molecular composition of radish oil and its lower heat of combustion, the following input data are required: the number of carbon, hydrogen and oxygen atoms in the molecule of each acid, the molecular weight of the acids, and the percentage of each acid in the radish oil.

Determination of elemental composition and lower heating value of radish oil and DST was carried out using the following methodology (in full author's calculation text for Ukhanov (2018)). Knowing the percentage content (r) of higher aliphatic acids and the number of atoms (x) of carbon, (y) hydrogen and (z) oxygen in each acid CxHyOz, we determine the average number of atoms of each element in natural radish oil using the formulas:

$$x_{av} = \Sigma x_i \cdot r_i \text{ ; } y_{av} = \Sigma y_i \cdot r_i\text{; } z_{av} = \Sigma z_i \cdot r_i. \quad (5.8)$$

Врезультатерасчета(безучетачислаатомовнеидентифицированного остатка) получаем:

$$x_{av} = 14 \cdot 0.0004+15 \cdot 0.0002+16 \cdot (0.0510+0.0011)+18 \cdot (0.0246+0.3216+ +0.2199+0.00001+0.1282)+20 \cdot (0.0089+0.0914+0.0042+0.0012)+ +22 \cdot (0.0040+0.1250+0.0015+0.0068)+24 \cdot (0.0103+0.0000) = 18.73;$$

$$y_{av} = 28 \cdot 0.0004+30 \cdot 0.0002+32 \cdot 0.0510+30 \cdot 0.0011+36 \cdot 0.0246+ +34 \cdot 0.3216++32 \cdot (0.2199+0.00001)+34 \cdot 0.1282+36 \cdot (0.0089+0.0914)+ +38 \cdot (0.0042+0.0012)+40 \cdot (0.0040+0.1250)+42 \cdot 0.0015+44 \cdot 0.0068+ +46 \cdot 0.0103+48 \cdot 0.0000 = 34.71;$$

$$z_{av}=2 \cdot (0.0004+0.0002+0.0510+0.0011+0.0246+0.3216+0.2199+ +0.00001+0.1282+0.0089+0.0914+0.0042+0.0012+0.0040+0.1250+ +0.0015+0.0068+0.0103+0.00) = 2.00.$$

Then the average chemical formula of the isolated acids of the radish oil will be $C_{18.73}H_{34.71}O_2$.

The author of the study (Ukhanov, 2018) determined the average molecular formula of radish oil:

$$3C_{18,73}H_{34,71}O_2+C_3H_5(OH)_3 -_3H_2O=_3C_{18.73}H_{34.71}O_2+C_3H_2.$$

Average molecular formula of radish oil $C_{59.19}H_{106.13}O_6$

Total molecular weights of each of the elements in radish oil:

$$\Sigma M(C) = M(C) \cdot x_{av} = 12.011 \cdot 59.19 = 710.931 \text{ g mol}^{-1};$$

$$\Sigma M(H) = M(H) \cdot y_{av} = 1.0079 \cdot 106.13 = 106.968 \text{ g mol}^{-1};$$

$$\Sigma M(O) = M(O) \cdot z_{av} = 15.9994 \cdot 6 = 95.996 \text{ g mol}^{-1}.$$

The average molecular weight of radish oil was determined by the formula

$$MOSRO = \Sigma M(C) + \Sigma M(H)+ \Sigma M(O)$$

$$MOSRO = 710{,}931 + 106{,}968 + 95{,}996 = 913{,}895 \text{ g mol}^{-1}.$$

Divide the total molecular weight values of all the carbon (C), hydrogen (H) and oxygen (O) atoms that make up the radish oil by the average molecular weight of the radish oil to obtain the relative fractions of carbon, hydrogen and oxygen:

$$C = \Sigma M(C)/ MOSRO =710.931/913.895 = 0.778;$$

$$H = \Sigma M(H)/ MOSRO =106.968/913.895 = 0.117;$$

$$O = \Sigma M(O)/ MOSRO =95.996/913.895 = 0.105.$$

Thus, the elemental composition of radish oil:

C = 0.778; H = 0.117; O = 0.105.

Further, we determined (Ukhanov, 2018) the elemental composition of the radish-mineral fuel in the ratios of plant and mineral components 25:75, 50:50, 75:25 and 90:10.

Viscosity (kinematic) and density were determined at 20°C experimentally using viscometer and areometer. The results of calculations and measurements are presented in Table 5.18.

Table 5.18

Elemental composition, lower heat of combustion, density and viscosity of investigated fuels (Ukhanov, 2018)

Type of fuel	Elemental composition			Low calorific value, MJ kg^{-1}	Density, kg m^{-3}	Viscosity, mm^2 s^{-1}
	C	H	O			
100%DF	0.870	0.126	0.004	42.40	830	4.2
100%OSRO	0.778	0.117	0.105	37.37	922	78.4
25%OSRO+75%DF	0.847	0.124	0.029	41.24	885	23.0
50%OSRO+50%DF	0.824	0.121	0.055	39.89	897	41.5
75%OSRO+25%DF	0.801	0.119	0.080	38.66	908	60.0
90%OSRO+10%DF	0.787	0.118	0.095	37.89	914	71.0

Note: C, carbon; H, hydrogen; O, oxygen.

The results of the research show that red oil has a significantly higher density and viscosity compared to the corresponding indicators of commercial mineral DF, but when the share of mineral fuel in the blended fuel increases, the difference in values decreases significantly. The lower heat of combustion of red oil is equal to 37.37 MJ kg^{-1}, which is 11.9% lower than the corresponding index of commercial mineral DF. When the share of mineral fuel in DCT increases, the lower heat of combustion increases. So, for example, for blended fuel 25%OSRO+75%DF it is equal to 41.24 MJ kg^{-1}, which is lower than the corresponding indicator of mineral fuel by only 2.8%.

Table 5.19

Comparative power, fuel-economic and environmental performance of diesel engine when operating on blended red-mineral fuel and mineral diesel fuel (Ukhanov, 2018)

Type of fuel	Diesel performance		
	effective power, kW	specific effective fuel consumption, g $k^{-1}Wh^{-1}$	smokiness, %
100%DF	56.1	252.4	45
25%OSRO+75%DF	53.5	272.9	41
50%OSRO+50%DF	53.0	279.3	39
75%OSRO+25%DF	52.4	286.3	48
90%OSRO+10%DF	52.0	292.3	51
90%OSRO+10%DF(US)	53.2	283.8	50

OSRO – oilseed radish oil; DF – diesel fuel; DF(US) – diesel fuel treated with ultrasound

Comparative results of bench tests of diesel engine (Ukhanov, 2018) when operating on blended radish-mineral fuel in the ratio of components 25%OSRO+75%DF, 50%OSRO+50%DF, 75%OSRO+25%DF, 90%OSRO+10%DF and 90%OSRO+10%DF(US) show that with the increase in the content of radish oil in the blended fuel there is a slight decrease in the effective power and increase in the specific effective fuel consumption (Table 5.19). Thus, when operating on blended fuel with the ratio of mineral and vegetable components 90:10, the effective power of the diesel engine decreased from 56.1 kW to 52 kW (by 7.9 %), specific effective fuel consumption increased from 252.4 g/kW-h to 292.3 g/kW-h (by 15.8 %) in comparison with operation of the diesel engine on mineral fuel. The minimum exhaust gas smokiness is noted at operation on blended fuel 50%OSRO+50%DF and makes 39 %, which is 15,4 % less than at operation of diesel engine on mineral fuel.

Treatment of blended fuel with ultrasound allows to improve the performance of the diesel engine. So at work of a diesel engine on blended fuel 90%OSRO+10%DF(US) the effective power increases on 2,3 %, specific effective fuel consumption and smokiness decrease on 2,9 % and 2 % accordingly in comparison with work of a diesel engine on blended fuel 90%OSRO+10%DF not treated by ultrasound.

Commercial mineral DF and blended fuel in the ratio of components 25:75, 50:50, 75:25, 90:10, 90:10 (UZ 44 kHz) were taken as the investigated types of motor fuels. The studied fuels are characterized by the following parameters (according to the results of Ukhanov, (2018)):

Commodity DF: lower heat of combustion Hz = 42.4 MJ/kg; elemental composition C = 0.870, H = 0.126, O = 0.004; density ρ20 = 830 kg m^{-3}; viscosity υ20 = 4.2 mm^2 s^{-1}.

Red oil: Hz = 37.37 MJ/kg; C = 0.778, H = 0.117, O = 0.105; ρ20 = 922 kg m^3; υ20 = 78.4 mm^2 s^{-1}.

Blended redbed-mineral fuel:

– 25%OSRO + 75%DF: Hz = 41.24 MJ/kg; C = 0.847, H = 0.124, O = 0.029; ρ20 = 885 kg m^3; υ20 = 23.0 mm^2 s^{-1}.

– 50% OSRO + 50%DF: Hz = 39.89 MJ/kg; C = 0.824, H = 0.121, O = 0.055; ρ20 = 897 kg m^3; υ20 = 41.5 mm^2 s^{-1}.

– 75% OSRO + 25%DF: Hz = 38.665 MJ/kg; C = 0.801, H = 0.119, O = 0.080; ρ20 = 908 kg m^3; υ20 = 60.0 mm^2 s^{-1};

– 90% OSRO + 10%DF: Hz = 37.89 MJ/kg; C = 0.787, H = 0.118, O = 0.095; ρ20 = 914 kg m^3; υ20 = 71.0 mm^2 s^{-1}.

As a result of comparative studies of the engine in bench conditions it is established (Ukhanov, 2018) that at operation of diesel engine D-243 at all investigated modes and blended red-oil-mineral fuel with different ratio of red-oil and mineral DF there is some deterioration of effective indicators of the diesel engine in comparison with operation on commercial mineral DF. Deterioration of indicators occurs as the content of cut oil in the blended fuel increases. So the decrease of effective power at work of the diesel engine in a nominal mode on a mixed fuel 90%OSRO + 10%DF has made 7,3 %, specific effective and hourly fuel consumption have increased accordingly on 6,3 % and 15,8 % in comparison with work of the diesel engine on mineral DF.

The analysis of ecological indicators of the diesel engine shows that when the share of red oil in the blended fuel increases up to 50 %, the exhaust gas smokiness decreases by 13.3 % (from 45 % to 39 %), and the content of carbon monoxide by 16 % (from 0.25 % to 0.21 %) in comparison with the operation of the diesel engine on mineral DF. With further increase in the proportion (more than 50 %) of red oil in the blended fuel, the environmental performance deteriorates.

The results of comparative diesel engine tests show that ultrasonic treatment of blended red oil-mineral fuel leads to improvement of diesel performance.

For example, the specific effective fuel consumption of a diesel engine running on a 90% OSRO + 10% DF (US) blended fuel increased by 12.4% compared to running the engine on mineral DF, while on untreated 90% OSRO + 10% DF blended fuel, the specific effective fuel consumption increased by 15.8% compared to running on mineral DF. The effective efficiency of a diesel engine running on a 90% OSRO + 10% DF (US) blended fuel is 1.8% higher than when running the engine on mineral DF.

Comparative studies of the tractor unit (MTZ-82 +PLN-Z-35) in operating conditions have shown that hectare fuel consumption increases as the percentage content of red oil in DST increases. So, when the diesel engine works on blended fuel 90%OSRO+10%DF its consumption is 25% more than when working on mineral DF. Operating speed, hourly productivity of the tractor unit and operating power of the diesel engine at work on blended fuel with mineral fuel are reduced insignificantly to 3,6 %; 3,8 % and 1,3 % respectively, in comparison with work on mineral fuel. The lowest exhaust gas smokiness is observed when the tractor is running on blended fuel 50%OSRO+50%DF and is equal to 31 %, which is 20,5 % less than when running on mineral DF. Ultrasonic treatment allowed to improve the studied operational indicators. Thus, when the diesel engine is running on blended fuel 90% OSRO + 10% DF (US) such indicators as operating speed (by 1.8 %), hourly productivity (by 2 %), operating power (by 0.6 %) increased and such indicators as hectare fuel consumption (by 3.4 %) and exhaust gas smoke (by 2.4 %) decreased in comparison with operation on non-treated blended fuel 90%OSRO + 10% DF.

As a result of comparative studies of the engine in bench conditions it is established that at work of diesel engine D-243 on all investigated modes and all kinds of blended red- mineral fuel some deterioration of effective indicators of the diesel engine in comparison with work on mineral DF is observed.

Deterioration of indicators occurs as the share of red oil in blended fuel increases. So the decrease of effective power at work of the diesel engine in a nominal mode on a mixed fuel 90%OSRO + 10%DF has made 7,3%, hourly and specific effective fuel consumption has increased accordingly on 6,3% and 15,8% in comparison with work of the diesel engine on mineral DF.

Analysis of the environmental performance of the diesel engine (Ukhanov, 2018) shows that when the share of cut oil in the blended fuel is increased to 50%, the exhaust gas smoke decreased by 13.3% (from 45% to 39%) and carbon monoxide content by 16% (from 0.25% to 0.21%) compared to diesel operation on mineral DF. With further increase in the proportion of red oil in the blended fuel, the environmental performance deteriorates.

The results of comparative engine studies (Ukhanov, 2018) of the diesel engine show that ultrasonic treatment of blended red-oil-mineral fuel leads to an improvement in diesel performance.

For example, the specific effective fuel consumption increased by 12.4 % when the diesel engine operated on blended fuel 90%OSRO+10%DF(US), whereas it increased by 15.8 % on untreated blended 90% OSRO+10% DF, compared to operation on mineral DF. The effective efficiency of diesel engine while running on blended fuel 90%OSRO+10%DF(US) is 1.8 % higher than that of diesel engine running on mineral DF.

The studies also showed that the environmental performance of a diesel engine improves when the content of radish oil in the fuel mixture is no more than 50 %: exhaust gas smoke is reduced by 21.4 %, and CO_2 concentration is reduced by 40 %. The greatest effect on environmental performance is achieved when the engine runs on a mixture of 25 % OSRO + 75 % DF. It was also found that the treatment of radish-mineral fuel with ultrasound has a positive effect on improving the environmental performance of the engine (Figures 5.4–5.7).

Based on the results obtained, the authors conclude that radish oil can be effectively used to prepare mixed diesel fuel. At the same time, the drop in tractor engine power does not exceed 7 %, and the increase in specific fuel consumption does not exceed 16 %. Ultrasonic treatment of mixed radish-diesel fuel improves these indicators by 2–4 %.

Thus, oil radish is not only a valuable fodder crop, but also a promising bioenergy crop, and by changing the parameters of oil radish cultivation

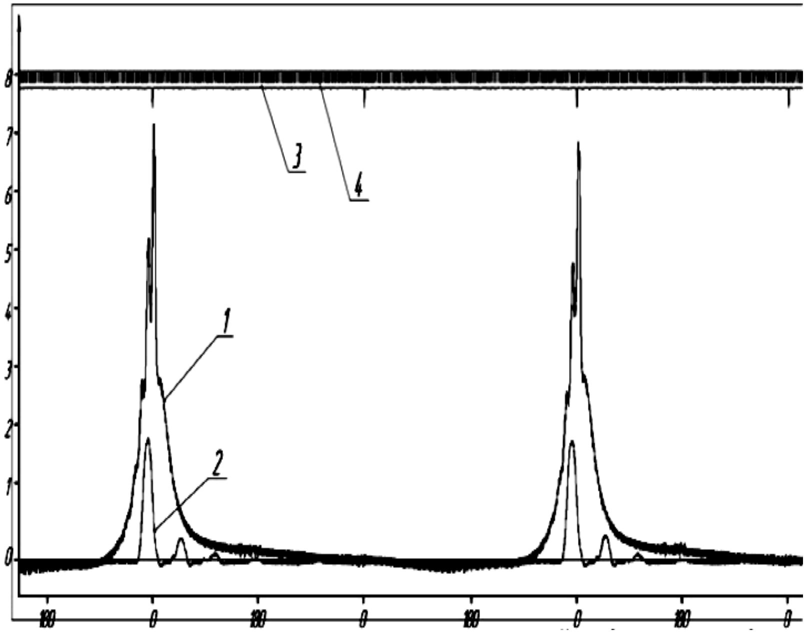


Figure 5.4 – Indicator diagram of the D 243 engine in the rated power mode at 25 % OSRO + 75 % DF: 1 – gas pressure in the cylinder, 2 – fuel pressure in front of the injector, 3 – upper dead center indicator, 4 – flywheel teeth indicator) (Ukhanov, 2018)

technology, it is possible to change the technological parameters of raw materials and regulate the "biofuel" productivity of a hectare of crops.

A comprehensive study of biodiesel from oil radish was conducted by Chammoun (2009). Two important properties for oilseed radish (Table 5.20) are iodine value and cold filter plugging point (CFPP).

The fatty acid profile identifies the carbon chain lengths and saturation of fatty acids in the triglycerides. It is important to note the high levels of 22:1, erucic acid, at 31.76% (Table 5.21).

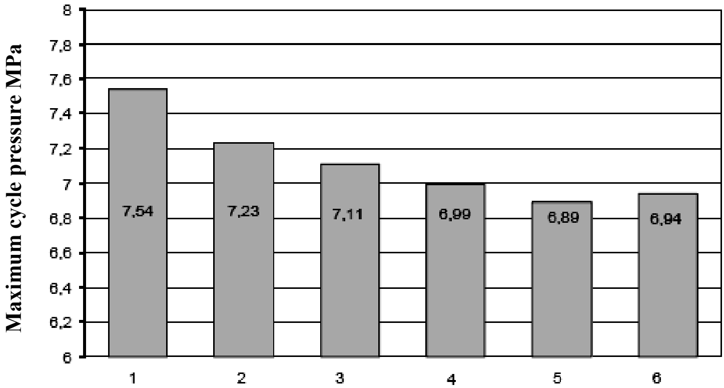


Figure 5.5 – Maximum engine cycle pressure (MPa) of the D-243 in the rated power mode when operating on diesel mixed fuels: 1 – 100% VA; 2 – 25 % OSRO + 75 % DF; 3 – 50 % OSRO + 50 % DF; 4 – 75 % OSRO + 25 % DF; 5 – 90 % OSRO + 10 % DF; 6 – 90 % OSRO + 10 % DF (US) (Ukhanov, 2018)

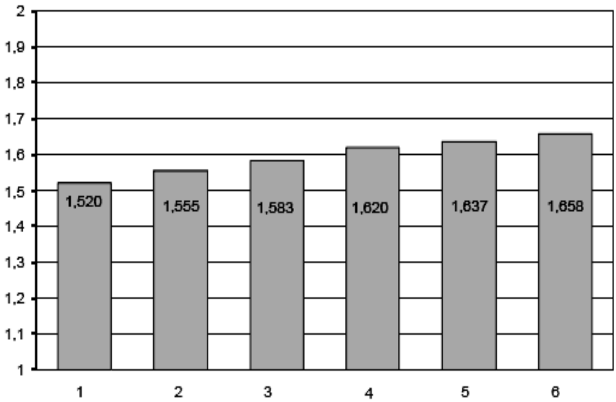


Figure 5.6 – Air surplus ratio of the D–243 engine in the rated power mode when operating on diesel mixed fuels: 1 – 100% VA; 2 – 25 % OSRO + 75 % DF; 3 – 50 % OSRO + 50 % DF; 4 – 75 % OSRO + 25 % DF; 5 – 90 % OSRO + 10 % DF; 6 – 90 % OSRO + 10 % DF (US) (Ukhanov, 2018)

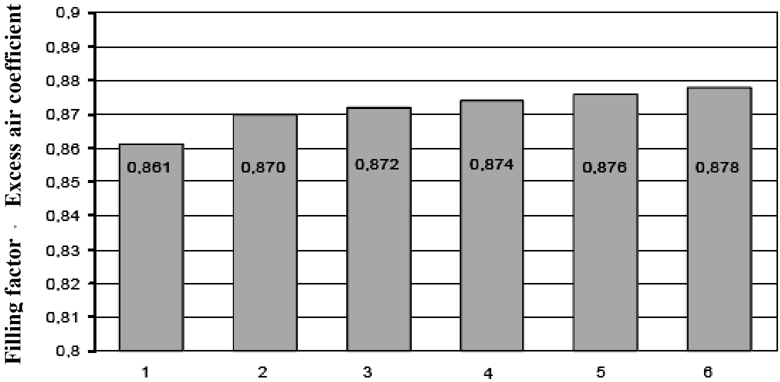


Figure 5.7 – Filling factor of the D–243 engine in the rated power mode when operating on diesel mixed fuels: 1 – 100% VA; 2 – 25 % OSRO + 75 % DF; 3 – 50 % OSRO + 50 % DF; 4 – 75 % OSRO + 25 % DF; 5 – 90 % OSRO + 10 % DF; 6 – 90 % OSRO + 10 % DF (US) (Ukhanov, 2018)

Table 5.20

Oilseed Radish B100 Fuel Properties (Chammoun, 2009)

Parameter	Unit	Test Method	Result	Limit
Total Glycerol	% (m/m)	EN 14105	0.108	< 0.24
Free Glycerol	% (m/m)	EN 14105	0.000	< 0.02
Monoglyceride Content	% (m/m)	EN 14105	0.301	< 0.80
Diglyceride Content	% (m/m)	EN 14105	0.027	< 0.20
Triglyceride Content	% (m/m)	EN 14105	0.000	< 0.20
Acid Value	mg_{KOH}/g	EN 14104	0.082	< 0.50
Sulfur Content	mg/kg	EN ISO 20846	0.790	< 10.00
Water Content	mg/kg	EN ISO 12937	68	< 500
Iodine Value	g/100g	EN 14111	97	< 120
Cold Filter Plugging Point (CFPP)	°C	ASTM 637199	6.0	Report

Rapeseed oil is considered non-edible oil because of the high levels of erucic acid. These levels were decreased by planting breeding and canola was developed. Canola is edible oil and is extensively in this capacity. If the erucic acid levels of oilseed radish were reduced, more uses of oilseed radish could develop while the presence of this oil lends it to unique industrial uses. It is also important to note that the remaining majority of the fatty acid profile is dominated by 18:1 (oleic acid) at 23.87%, 18:2 (linoleic acid) at 13.46%, and 18:3 (linolenic acid) at 10.34%.

Table 5.21

Fatty Acid Profile of Oilseed Radish Oil (Chammoun, 2009)

Fatty Acid (n=3)	Percent (%)
16:0	6.13
16:1	0.05
18:0	1.68
18:1	23.87
18:2	13.46
18:3	10.34
20:0	0.68
20:1	8.58
22:0	1.64
22:1	31.76
24:0	0.61
24:1	1.26
Saturated	10.74
Monounsaturated	65.51
Polyunsaturated	23.75

The coking indices for oilseed radish B100 and B20 both average 1.2 (Table 5.22). This is higher than the index of No. 2 diesel fuel, D2, of one. Usually biodiesel subjected to this engine stress test yield coking indices less than one. Results higher than one indicate this biodiesel may perform slightly less desirable than D2 and other biodiesel suggesting possible pre-mature wear on engine parts. To test for true differences between the biodiesel and D2, statistical analysis was done on the differences (delta) of the dirty and clean injectors. This difference is proportionate to the actual amount of coke deposited during the engine test. These deltas are also the numbers used to calculate the coking indices. The deltas are in six groups, D2A, D2B, B100A, B100B, B20A, and B20B. Two sample F tests were performed to determine if the variances of the six groups were statistically different. Since no differences were detected in the variances of the six groups, an Analysis of Variance (ANOVA) assuming equal variance was performed to detect statistical differences in the mean of the six groups. From the statistical analysis of the difference in areas of the coking on the injectors, there is no statistical difference in means of the six groups. Although the coking index for B20 and B100 oilseed radish biodiesel is higher than one, statistically there was no difference in the amount of coking on the injectors when biodiesel was tested over the baseline of D2. The coking index provides a quick assessment of the fuels performance, but the ANOVA gives actual differences between the groups. Statistical analysis is done on the deltas and not the coking indices because the coking indices do not allow for the variance of the D2 engine tests to be used in the analysis, since it is divided by itself to give a CI of one.

Table 5.22

Coking Indices for Oilseed Radish Biodiesel (Chammoun, 2009)

Engine Test	B100 Coking Index	B20 Coking Index
1	1.1	1.3
2	1.3	1.3
3	1.1	0.86
Average	1.2	1.2

The fuel consumption of D2 was observed to be less than that of B100 but not B20 (Table 5.23). A two sample F test was done on the six groups' recorded fuel consumptions, and a difference in variances was detected between the groups. The variances for B20A and B20B were the lowest at 308 and 933 respectively. The variances for B100A and B100B were 4008 and 25833; the variances for D2A and D2B were 33956 and 21683 respectively. The differences in variances were too large to continue the analysis with ANOVA, so the average fuel consumptions are displayed graphically (Figures 5.8–5.9).

The average emissions data for each fuel is presented graphically according to engine RPM when running at full throttle. If gas sensors were not operable, no data is presented for that fuel and the number (n) used in averaging is also reported. CO_2 emissions were recorded for one test each of D2 and B100, no B20 was recorded. A steady increase is CO2 is seen as loading on the engine increases. More CO2 output is the result of more fuel being combusted.

Table 5.23

Fuel Consumption Indices for Oilseed Radish Biodiesel (Chammoun, 2009)

Engine Test	B100 Fuel Consumption Index	B20 Fuel Consumption Index
1	1.0	1.0
2	1.2	1.0
3	1.3	1.0
Average	1.2	1.0

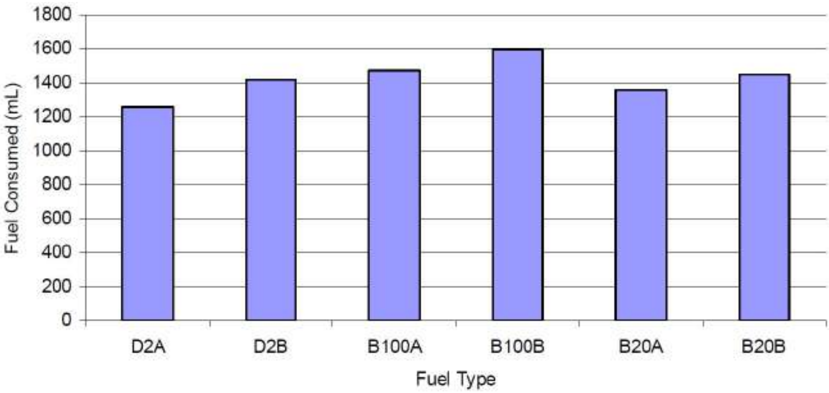


Figure 5.8 – Average Fuel Consumption for Engines A and B using D2, B20, and B100B Oilseed Radish Biodiesel (Chammoun, 2009)

A rapid jump in CO_2 emissions (Figure 5.10) is seen at the heavy engine loadings when more fuel is being consumed. As more fuel is consumed, more carbon is released thus the levels of CO increase. The increased in B100 CO emissions at heavier loadings is more than that of D2 or B20.

NOx emissions (Figure 5.10) show a marked increase of NOx in B100 over that of B20 and D2. This is what is typically reported in the literature, that biodiesel NOx emissions will increase over D2. But, this is the first time we have seen an increase in NOx in our engine testing. NO emissions and NOx emissions are essentially identical.

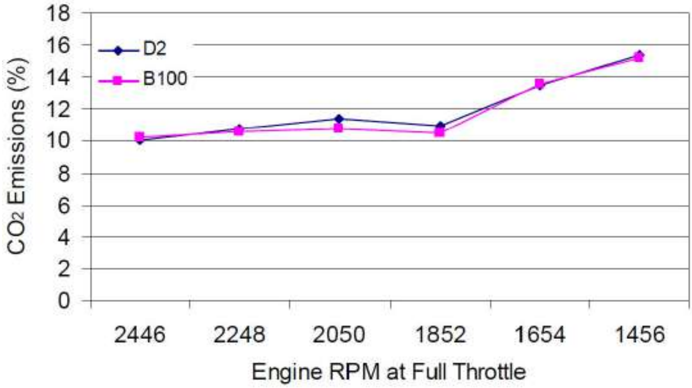


Figure 5.9 – CO_2 Emissions of D2, B20, and B100 Oilseed Radish Biodiesel (n=3) (Chammoun, 2009)

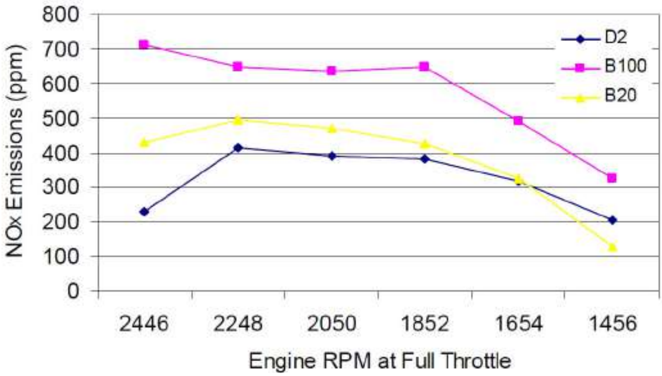


Figure 5.10 – NOx Emissions of D2, B20, and B100 Oilseed Radish Biodiesel (n=3) (Chammoun, 2009)

C_xH_y emissions (Figure 5.11) are reported at one run each for D2 and B100, no data was recorded for B20. C_xH_y emissions report hydrocarbon levels in fuel emissions. This would include any uncombusted fuel contained in the exhaust gases. Levels of hydrocarbons increase drastically at heavy loadings of the engine. This result is due to larger amounts of fuel consumption at the heavier loadings of the engine.

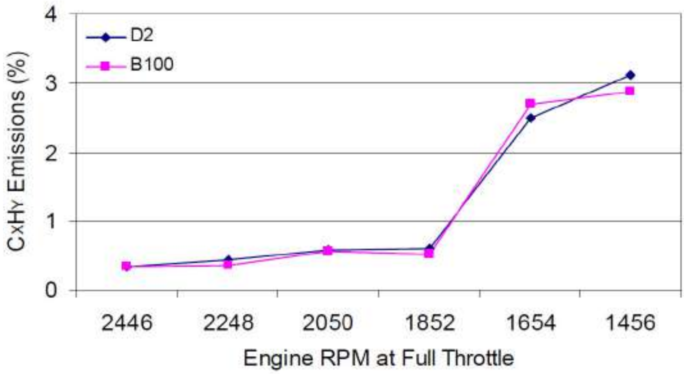


Figure 5.11 C_xH_y Emissions of D2 and B100 Oilseed Radish Biodiesel (n=1) (Chammoun, 2009)

From the plots of iodine number versus CFPP, it does not appear that any trend can be observed in the plot. The R-squared values are too low to indicate a significant trend. Although, it is notable that when oilseed radish and crambe are removed from the data set and it is replotted, the linear, logarithmic, and 2nd order polynomial trends improved based on the R-squared values. For these plots the oilseed radish data is from this study (Table 5.24, Figure 5.12), CFPP data is from Mittelbach and Remschmidt (2004), and iodine values are from Eckey (1954).

Table 5.24

Iodine Numbers and CFPP Temperatures for Vegetable Oils and Their Fuels (Chammoun, 2009)

Oil/Fuel	Iodine Number	CFPP
Oilseed Radish	97	6
Soybean	131.6	-2
Sunflower	132.5	-3
Camellina	140.5	-1
Tall Oil	129.5	-7
Castor	86	-3
Crambe	100	8.5
Olive	84.5	-6
Poppy Seed	137	-1

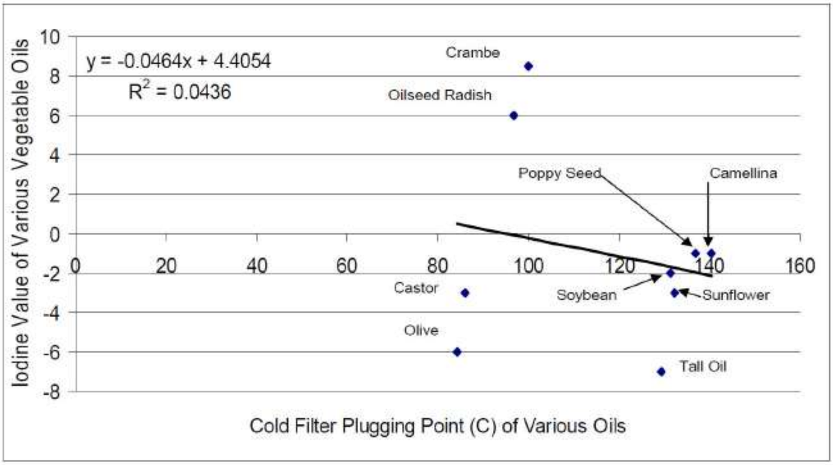


Figure 5.12 – Linear Plot of Iodine Number vs. CFPP without Oilseed Radish and Crambe (Chammoun, 2009)

From the crush results it can be concluded that oilseed radish can adequately be crushed using a screw type press in a one stage cold crush. With an average oil yield of 28.8%, the majority of the oil was extracted using only the cold crush. More oil could be obtained using either a second stage cold crush of the residual meal, or adding a solvent extraction step to the residual meal. It is believed more oil could be extracted from the cold crush if the process were optimized for oilseed radish seed size. Increasing the temperature of the seed would also yield more oil from the cold crush.

Fuel properties results indicate that it is possible to meet ASTM and EU standards for biodiesel using oilseed radish oil as a feedstock. The CFPP number for oilseed radish oil based biodiesel is high and would be a problem if a cold flow specification level was set. Currently CFPP is required to be reported and no threshold is set. If a threshold level is set, it is likely that oilseed radish cold flow would not ASTM or European standards. It is possible that future research on oilseed radish could lead to varieties that yield better CFPP numbers. Through plant breeding, more desirable cold flow properties could be bred into the crop for its use as a biodiesel feedstock. The high level of erucic acid seen in the fatty acid profile of oilseed radish is similar to that of rapeseed, a European biodiesel feedstock. Human toxicity of erucic acid will keep oilseed radish oil out of the food market, and thus improve its fit as a dedicated energy crop. Just as in cold flow properties, the levels of erucic acid could be decreased through plant breeding. Similar techniques were used to breed canola from rapeseed. Future work in this area could create additional markets for the crop.

Oilseed radish B100 and B20 shared a coking index of 1.2, although B100 would have been expected to have a higher coking potential than B20. Typically biodiesel produces lower coking indices than petroleum diesel; our results were contrary to this behavior. From the statistical analysis of coking deltas, there was not a statistical difference in the means of the deltas between any of the six groups; i.e. statistically each fuel performed on the same level. B100 or B20 from oilseed radish can be used in diesel engines without a statistical decrease in performance of the engine. Based on the fuel consumption indices, B20 performed the same as D2 and B100 performance was slightly less desirable at 1.2. But, since the variances within D2 and B100 were so high, further statistical analysis was determined to be unnecessary and coking indices are used to judge fuel consumption performance. Emissions data were not consistent enough for statistical analysis due to problems with gas sensors in the emissions testing equipment. For this reason the emissions data are presented as averages (if values were present) in graphs as a progression of loading and decreasing engine revolutions per minute (rpm). A relationship between iodine value and CFPP was determined to be less significant than predicted. When oilseed radish and crambe were removed from the plot, the r-squared value improved five fold. The leads us to believe that even though strong relationship was not established, oilseed radish and crambe lay outside the norm of other oils plotted. Both had high CFPP values, yet relatively low iodine values. The r-squared values lead us to believe that the relationship is more complex than originally believed. More research should be conducted to determine the relationship, if it exists, between cold flow and saturation of vegetable oils. One method would be to attempt the same analysis using pure triglycerides. If a relationship can be determined, a biodiesel from a particular vegetable oil can have a CFPP predicted before the oil is ever converted to biodiesel. This could serve as a rapid analysis for potential cold flow properties of a particular biodiesel feedstock.

There is need for future research into the agronomics of oilseed radish. Field trial should be done to quantify the agronomic benefits this crop has to offer in Georgia. Dr. Wilson Faircloth at the United States Department of Agriculture's National Peanut Research Laboratory in Dawson, Georgia is leading the effort to establish oilseed radish field trials. Dr. Faircloth reports excellent germination and crop growth throughout the cool season. Dr. Faircloth estimates harvest in adequate time to follow with a warm season crop. Although one season is not enough data to make any conclusions on the growth of the plant, it is a starting point in which future studies should be continued to assess the agronomic potential of oilseed radish. Since oilseed radish adds value to a cropping system as a cover crop, more research should be done to quantify these benefits and account for them along with the value of the oil for biodiesel feedstock. We believe that focusing attention on biofuel crops that have additional benefits to cropping systems in the form of improved soil fertility, pest protection, and soil health, is a route that should be pursued in future biofuel research. With the ever-changing dynamic of world fuel prices, additional value in a biofuel crop will increase the crop's ability to withstand large fluctuations in the fuel market. Added agronomic benefits also increase a producer's desire to grow a particular crop. Energy crops with agronomic benefits that can be used in crop rotations, lead to more sustainable farming practices and money savings to producers.

Oilseed radish oil was extracted, biodiesel produced and analyzed, and performance testing completed. The results verify that oilseed radish biodiesel meets ASTM and European standards, and performance testing concludes oilseed radish performs on the same level as petroleum diesel.

According to Chammoun (2009) to evaluate economic feasibility all costs and returns must be calculated. Costs and returns are calculated on a per acre basis using a yield of 1200 pounds of oilseed radish seed production per acre. The costs and returns calculated are not actual costs and returns, but hypothesized costs and returns based on available data. For actual costs and returns, experimental data should be acquired from growth studies. The costs and returns calculated here assume a low input situation, i.e. planting and harvesting the crop only, no other production costs considered. Hypothesized Costs for Oilseed Radish. Seed costs consisted of $66.93 per acre with an additional cost of $15.00 per acre for planting and $36.25 per acre for harvesting the seed. A minimum input system is used during production; therefore no additional inputs were calculated for crop production. It is assumed that oilseed radish can be planted into the previous crop's residue without any additional soil preparation. At a seed crushing cost of $50.00 per ton, oilseed radish would cost $30.00 per acre; yielding 346 pounds of oil (28.8%) and 854 pounds of meal (71.2%) per acre. At a refining and degumming cost of $0.025 per pound, it would costs $8.64 per acre to refine and degum the oil. With oil to biodiesel yield of 96% and 7.5 pounds of oil per gallon, production would be 42.5 gallons of oil per acre. With biodiesel production costs of $0.70 per gallon of oil, $30.97 per acre would be the production cost for biodiesel. Total hypothesized costs per acre sum to $187.78. These calculations assume no loss in processing oilseed radish into crude oil and biodiesel. Additional costs not included could be fertilizer required to grow the crop in Georgia, pesticides required to limit pest damage, and additional labor costs. Since hypothesized costs are simplified, actual costs may be greater than hypothesized costs (Table 5.25).

In the third case, to produce biodiesel, seeds purchased from Johnny's Select Seeds of Winslow, Maine were crushed to obtain crude oil. Oil yield was 28.8% by weight (Chammoun, 2009); the remainder was in meal.

The oil was then centrifuged and degummed. The degummed oil was then successfully converted into biodiesel by transesterification. Growers of oilseed radish in the Willamette Valley of Oregon report yields ranging from 1200 pounds/acre to over 2000 pounds/acre depending on management practices. More intensely managed crops produce more seed yield. A yield of 40% oil by weight, gives a range of 64 to 107 gallons of oil per acre (7.5 pounds per gallon). At the experimental yield of 28.8% oil, the range of oil per acre is 46 to 77 gallons. It is important to note that this oil yield will be in addition to any warm season crop that is grown in rotation with oilseed radish. In a biofuels rotation designed to maximize oil production per acre, a warm season oilseed crop could be grown, i.e. peanut or soybean and then oilseed radish grown in the cool season to supplement the amount of oil produced per acre per year. Methodology of Economic Analysis.

Table 5.25

Amino Acid Profile of Oilseed Radish Meal (Chammoun, 2009)

Amino Acid	W/W% g per 100 g sample (average n=2)
Taurine	0.03
Hydroxyproline	0.22
Aspartic Acid	2.13
Threonine	1.35
Serine	1.13
Glutamic Acid	5.43
Proline	1.99
Lanthionine	0.00
Glycine	1.78
Alanine	1.45
Cysteine	0.92
Valine	1.64
Methionine	0.62
Isoleucine	1.25
Leucine	2.23
Tyrosine	0.95
Phenylalanine	1.26
Hydroxylysine	0.04
Ornithine	0.02
Lysine	1.83
Histidine	1.00
Arginine	2.43
Tryptophan	0.39
Total	30.04

Hypothesized returns were calculated from crop and biodiesel byproducts, and from savings of insecticides that would not be applied (to subsequent crops) based on the nematode controlling capabilities of oilseed radish. A 92% reduction in nematode populations was observed in field studies, therefore it is assumed that no additional nematode control would be needed after a crop of oilseed radish was produced. There is currently no market for oilseed radish meal. A potential value for oilseed radish meal is calculated using the crop's crude protein value of 35%. Making the assumption that the price of soybean is composed solely of its protein content and that oilseed radish meal can be priced proportionately; a 48% protein soybean meal price of $222.27 per ton would give a hypothesized oilseed radish meal price of $162.07 per ton. At the yield of 1200 pounds per acre of oilseed radish, $69.24 per acre is the hypothesized value of the meal. With a five year average price of $3.27 for biodiesel, potential biodiesel returns would be $138.87 per acre. A five year average crude glycerin price of $0.07 per pound and a yield of 10.59% glycerin, glycerin value per acre would be $2.46. A hypothesized savings of $18.24 per acre and $15.20 per acre would be saved on insecticide (aldicarb) and insecticide application costs, respectively. An application rate of 6 pounds of aldicarb per acre was used for nematode control based on the recommendation of the University of Georgia Extension Plant Pathologist cotton budget for soil pathogen control. A total return of $244.00 per acre leaves the overall system with a hypothesized net return of $56.22 per acre. With a net biodiesel value of $107.90 per acre and an oil yield of 346 pounds per acre, an implied oil value of $0.31 per pound can be obtained. The implied value is the price that can be paid to the producer for crude oilseed radish oil so that a breakeven point can be achieved in biodiesel production. This value is not so important since there is currently no market for oilseed radish oil, but it is provided as a means to compare with other vegetable oil prices. Additional returns that were not included, but may add value to the system, could be weed suppression, soil aeration, soil compaction reduction, and nitrogen trapping. In an actual costing situation, these benefits would need to be assigned an economic value and that value assessed. These values are important, but detailed studies are needed to quantify them. Since these benefits are not included, hypothesized returns calculated may be lower than actual returns.

Sensitivity analyses were done on seed costs, biodiesel price, meal price, total costs, and total returns. It is believed that lower seed costs would be available to growers once markets for oilseed radish were established. By subtracting a total hypothesized cost per acre without seed of $120.86 from total hypothesized returns of $244.00, a minimum breakeven seed cost of $123.14 per acre, or $4.93 per pound of seed, would be needed to return adequate money to pay for all costs. A seed sensitivity graph is obtained from the break even seed cost and the hypothesized seed cost per acre (Table 5.26, Figure 5.13–5.15).

Fuel prices change on a daily basis. For this reason it is necessary to calculate a hypothesized break even price for biodiesel. A hypothesized break even price for biodiesel can be obtained by subtracting hypothesized returns without biodiesel ($105.14) from total hypothesized costs ($187.78) and dividing by biodiesel production per acre (42.5 gallons). The hypothesized break even price for biodiesel would be $1.94 per gallon. This means the biodiesel price could decrease below the $3.27 level (but above $1.94), and net hypothesized returns would remain positive.

Table 5.26

Hypothesized Costs and Returns for Oilseed Radish at 1200 lbs/acre yield and Low Input Growing System (Chammoun, 2009)

Hypothesized Costs				
Activity/Product	**Unit**	**Number of Units**	**Price per Unit ($)**	**Price per Acre ($)**
Seed	Pound	50	133.85	66.93
Planting	Acre	1	15	15
Harvest	Acre	1	36.25	36.25
Seed Crushing	Ton	0.6	50	30
Refining/Degumming	Pound	346	0.025	8.64
Biodiesel Production	Gallon	42.5	0.7	30.97
Total Hypothesized Costs				187.78
Hypothesized Returns				
Meal	Ton	0.427	162.07	69.24
Biodiesel	Gallon	42.5	3.27	138.87
Glycerin	Pound	35.1	0.07	2.46
Aldicarb	Pound	6	3.04	18.24
Aldicarb Application	Acre	1	15.2	15.2
Total Hypothesized Returns				244.00
Total Hypothesized System Value				56.22

Soybean meal prices change on a daily basis, and it is assumed that the hypothesized meal price for oilseed radish could change regularly as well. Because of this possibility it is important to calculate a hypothesized break even price for oilseed radish meal. The hypothesized break even price for the meal is calculated by subtracting total hypothesized returns without the meal ($174.77) from total hypothesized costs ($187.78) and dividing it by the amount of oilseed radish meal per acre (0.4272 tons). The hypothesized break even meal price for oilseed radish is $30.45 per ton.

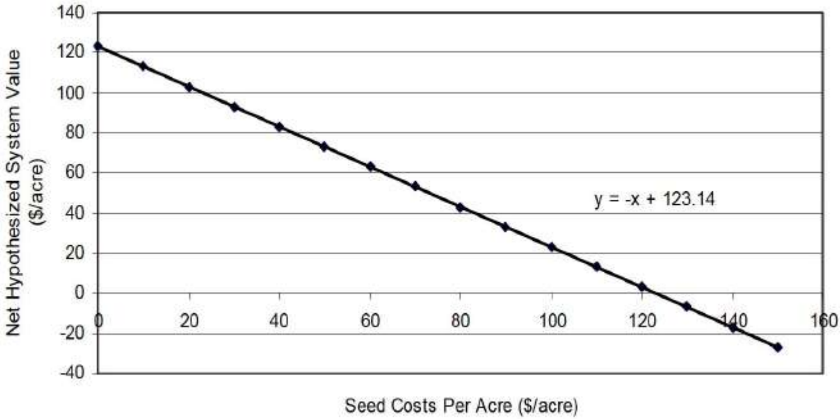


Figure 5.13 – Sensitivity of Net Hypothesized System Value to Seed Costs Variation when Planting 25 lbs/acre (Chammoun, 2009)

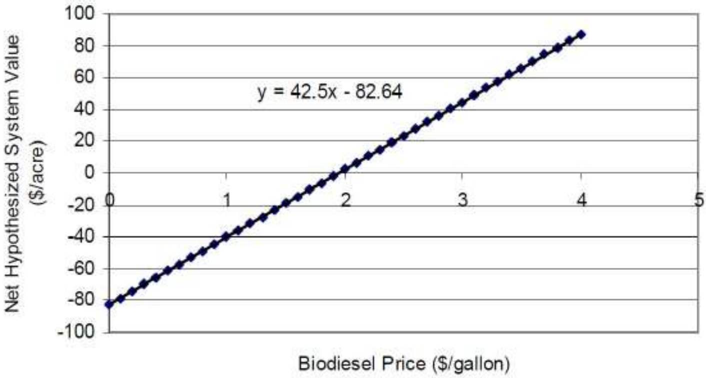


Figure 5.14 – Sensitivity of Total Hypothesized System Value to Biodiesel Price Variation (Chammoun, 2009)

Since many assumptions were made for this analysis it is possible that additional costs would be needed to produce the crop, or that additional returns could be generated from the crop. For this reason, a range of 20% was used to evaluate costs and returns if each were 20% higher or 20%

lower. If hypothesized costs were 20% higher, hypothesized returns would be adequate to cover hypothesized costs (Table 5.27). If hypothesized returns were 20% lower, hypothesized costs would not exceed the lowered hypothesized returns (Table 5.28). In fact, hypothesized costs would need to increase by approximately 30% to reach a breakeven point. In the same way, hypothesized returns would need to decrease by 23% to reach a breakeven point.

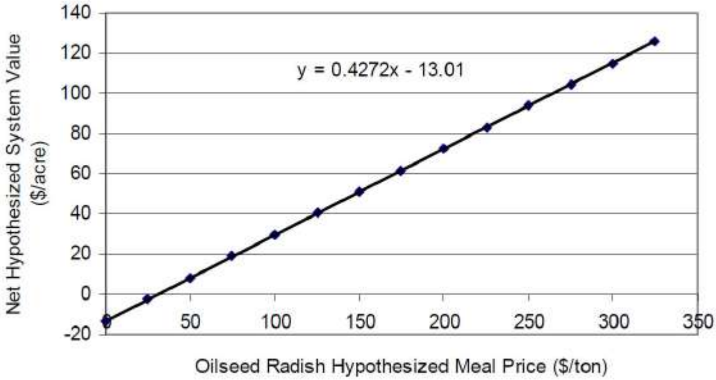


Figure 5.15 – Sensitivity of Total Hypothesized System Value to Meal Price Variation (Chammoun, 2009)

Table 5.27

(+-) 20% Variation in Hypothesized Costs (Chammoun, 2009)

Variation (%)	Returns ($)	Costs ($)	Net ($)
-20	244.00	150.22	93.78
-10	244.00	169.00	75.00
0	244.00	187.78	56.22
10	244.00	206.56	37.44
20	244.00	225.34	18.66

The author of this study (Chammoun, 2009) concluded that a hypothesized net return of $56.22 per acre, oilseed radish demonstrates potential to be a viable crop in Georgia, based on the assumptions made. An implied oilseed radish oil value based on biodiesel production of \$0.31 per pound was hypothesized, and a hypothesized meal value was determined to be \$69.24 per acre. A total hypothesized savings of \$33.45 per acre could also be obtained when growing the next economic crop in rotation with oilseed radish if nematode populations were harmful.

Table 5.28

(+-) 20% Variation in Hypothesized Returns (Chammoun, 2009)

Variation (%)	Returns (\$)	Costs (\$)	Net (\$)
-20	195.20	187.78	7.42
-10	219.60	187.78	31.82
0	244.00	187.78	56.22
10	268.41	187.78	80.63
20	292.81	187.78	105.03

A hypothesized break even cost for seed was determined to be \$123.14 per acre which is above the hypothesized seed cost of \$66.93 per acre. This difference in hypothesized value demonstrates that hypothesized seed costs could increase by approximately 84%, and a break even point still achieved. It is believed that seed costs would actually decrease after one year of growth. Seed could be saved by the producer to supplements seed for next year's crop. It is also believed that once more growers produce oilseed radish as a crop, the seed costs will decrease. The hypothesized break even biodiesel price was calculated to be \$1.94 per gallon. The hypothesized break even biodiesel price is approximately 41% below the five year average price of \$3.27 per gallon. The hypothesized breakeven price is useful to compare with current fuel prices to judge on the potential for oilseed radish biodiesel to be competitive in the biodiesel market. The hypothesized break even price for oilseed radish meal was calculated to be \$30.45 per ton. This is below the hypothesized meal value of \$162.07 per ton that is based on protein content. The large gap between the two prices demonstrates that the hypothesized meal price (\$162.07 per ton) could decrease by 81% and hypothesized returns would still exceed costs.

Due to the limitations of the hypothesized calculations, a 20% variation in hypothesized costs and returns was calculated. If there was a 20% increase in hypothesized costs, and no increase in returns, hypothesized returns would still be greater than hypothesized costs. If there was a 20%

decrease in hypothesized returns, and no decrease in costs, hypothesized returns would still exceed hypothesized costs. This indicates improved potential for oilseed radish to succeed as a crop in Georgia. Even with a decrease in hypothesized system value, oilseed radish remains an attractive crop due to the un-valued benefits the crop can provide. Although values for soil aeration, soil compaction reduction, weed suppression, and nitrogen trapping may not be high, there is still added value in each of these benefits when oilseed radish is used in a crop rotation.

Oilseed radish meal also had high fat value, giving it a high energy value. The high fat value is due to the cold crush extraction method used, and no additional solvent extraction. The high fat content would increase the value of oilseed radish meal, and therefore increase the total hypothesized value of the system. More detailed studies are needed to allow for a more accurate method of evaluating the potential value of oilseed radish meal. Agronomic benefits should be evaluated with field studies done in Georgia to confirm nematode control levels, weed suppression levels, nitrogen trapping, soil aeration, and soil compaction reduction levels. Quantifying these additional benefits in Georgia soils, would allow for an economic evaluation to be done and a hypothesized value to be assigned, increasing the accuracy of the economic evaluation and adding value to the system.

Hypothesized costs and returns are limited by the assumptions used to calculate them. These assumptions were made in the absence of specific data for oilseed radish in Georgia. Oilseed radish is a new crop to Georgia; therefore no data was available for calculations. Assumptions were made based on data from other parts of the United States. Future studies are needed to gather data on oilseed radish in Georgia. The hypothesized system value shows potential for oilseed radish to succeed as a cover crop and biodiesel energy crop in Georgia. More importantly, crops such as oilseed radish should be considered in future crop rotations for their agronomic benefits and potential energy value. It is believed that energy crops with agronomic benefits will lead to more sustainable biofuel production, increased producer returns, and improved environmental health.

Oilseed radish as a feedstock for biodiesel was also highly evaluated in the study by Valle et al. (2009). The author concluded that oilseed radish – *Raphanus sativus* L. var. *oleiferus* Stokes – oil has been regarded as an interesting option to produce biodiesel, because the oil cannot be used for human consumption, the seeds have high oil content, and the cost of production is low. Furthermore, the plant has been used for green fertilization during the interval between harvests of other crops, due to its rapid development as well as its great ability to recycle nutrients. The content of free fatty acids in the crude oil is less than 0.5%, which makes it appropriate for basic catalyzed synthesis. However, basic catalyzed synthesis is very sensitive to the presence of water in the reaction environment. This study proposes the optimization of biodiesel synthesis using sodium ethoxide (sodium ethylate) as a catalyst, with the purpose of minimizing water formation during reaction, increase efficiency, and thus carry out transesterification in a single step. Ethanol was used instead of the methylic route, aiming at the production of an entirely renewable and environmentally preferable fuel. The experiments were proposed and carried out using a combination of fractional factorial design and Doehlert design, in order to allow an extensive study of the process variables with a minimum of experiments. Very intense levels of agitation and high temperatures proved to be inadequate to reach an effective reaction. At optimum conditions the ester content reached approximately 97.9%, which along with several other physical chemistry assays confirm the good quality of the product and that the synthesis of fodder radish crude oil can be performed in a single step efficiently.

The molar mass of fodder radish oil was calculated as 900.32 g mol^{-1} based on its fatty acid composition shown in Figure 5.16 and Table 5.29 and on the acid number (0.7182 mgKOH $goil^{-1}$) determined by potenciometric titration.

Table shows some physical chemistry properties of the biodiesel from fodder radish oil obtained in our experiments that were performed according to the respective standard methods. All these analyses were carried out in triplicate, and the reported values are the average of the results. These results are in accordance with Brazilian legislation for biodiesel commercialization in the country and are strong evidence of the good quality of the product. The high ester content in the purified product (97.9%) shows that the reaction was very efficient, and it is important for the high performance of diesel engines.

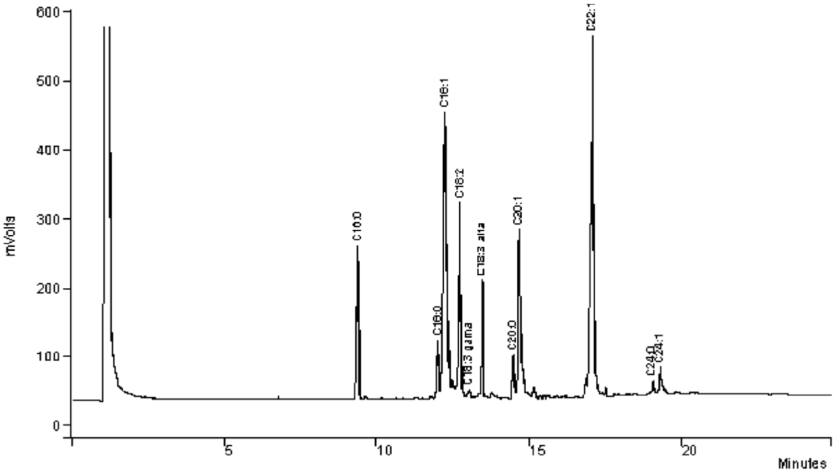


Figure 5.16 – Chromatogram of Raphanus sativus L. var. Oleiferus Stokes oil fatty acids analyzed as methyl esters by gas chromatography using a capillary column (DB-Wax, 30 m x 0.25 mm i.d., 0.25 m, J&W Scientific). Detector (FID) and injector (split 1:100) at 260 °C. The FAMES were identified by comparing retention times to a standards mix (Supelco37) (Valle et al., 2009)

Table 5.29

***Raphanus sativus* L. var. *oleiferus* Stokes Oil Fatty Acids (Valle et al., 2009)**

Composition			
fatty acid	**CN:DB[a]**	**ret. time (min)**	**composition (% w/w)**
palmitic	16:0	9.4	7.0
stearic	18:0	12.0	3.6
oleic	18:1	12.2	27.9
linoleic	18:2	12.7	7.6
linolenic	18:3	13.5	4.6
arachidic	20:0	14.5	2.2
gadoleic	20:1	14.7	11.2
erucic	22:1	17.1	33.3
lignoceric	24:0	19.1	0.6
nervonic	24:1	19.3	2.0

[ó] CN = carbon No.; DB = double bond

The specific gravity of 872.1 kg m^{-3} and the kinematic viscosity of 5.511 mm^2 s^{-1} guarantee that the fuel flows smoothly through the engine; it avoids excessive compression in the fuel injection pump and provides appropriate atomiza-tion in the combustion chamber, thus contributing to an efficient burning and to the low carbon deposits in the combustion area. This is confirmed by the result (0.03% w/w) of the carbon residue test (Table 5.30).

Table 5.30

Phisical Chemistry Properties of Biodiesel from Fodder Radish Oil (Valle et al., 2009)

properties aspect		**Brazilian specification**	**results LII[a]**	**methodology visual**
ester content	(% w/w)	minimum 96.5%	97.9	EN 14103
specific gravity at 20 °C	(kg/m^3)	850—900	872.1	ASTM D 4052
kinematic viscosity at 40 °C	(mm^2/s)	3.0-6.0	5.511	ASTM D 445
flash point	(°C)	minimum 100[b]	157.2	ASTM D 93
cold filter plugging point	(°C)	maximum 19	5	ASTM D 6371
carbon residue	(% w/w)	0.05	0.03	ASTM D 4530
copper corrosion, 3 h at 50 °C		maximum 1	1a	ASTM D 130
Na + K	(mg/kg)	maximum 5	1.774[c]	ABNTNBR 15556
Ca + Mg	(mg/kg)	maximum 5	1.509	
P	(mg/kg)	maximum 10	0.446	
acid number	(mg KOH/g)	maximum 0.5	0.21	ASTM D 664
iodine value	(g/100 g)	report	96	EN 14111

[a] Limpid and free from impurities.[b] If the flash is higher than 130 °C, it will not be necessary to determine the ethanol content.[c] This figure refers to Ca, because K was not determined.

The flash point was 157.2 °C. It indicates the temperature at which fuel vapors create a flammable mixture with atmospheric air, and it is important for safety in transport, storage and handling of fuel.

According to Brazilian laws, when flash point value is higher than 130 °C, the content of alcohol does not need to be determined. In this work, although the alcoholic content was not determined, the low values of Na (1.774 mg kg^{-1}) and Ca + Mg (1.509 mg kg^{-1}), as well as of the acid value (0.21 mg KOH g^{-1}) confirm the efficiency of the purification process, which aimed at removing the excess of alcohol, acid, and salts, as well as soaps and catalyst residues in the biodiesel. Copper corrosion test (1a) showed the low corrosiveness of the fuel, hence guaranteeing the integrity of the metallic parts of the engine. This result reveals the absence of sulfur components in the biodiesel.

Finally, the cold filter plugging point is a measure of the performance of fuel at low temperatures, and it is used as a handling indicator at low temperatures in the big flow tanks and in refinery and terminal pipelines. The result equal to 5 °C obtained for biodiesel from oilseed radish was far below the maximum limit (19 °C) established by Brazilian legislation.

The author of this study (Valle et al., 2009) concluded that the basis of the results achieved, it may be concluded that the use of sodium ethylate should be considered an interesting catalyst to the ethanolysis of fodder radish crude oil (Raphanus sativus L. var. oleiferus Stokes) because it reduces water production during the reaction and increases the efficiency of the transeseterification.

All the variables that affect the synthesis of biodiesel were studied: temperature, time, molar ratio, stirrer speed, and catalyst concentration. In the first stage of the work, the use of the 2(5–11) FFD showed that it is efficient in helping to select the most important variables, and allowed the reduction of the number of experiments at this stage. For the next stage, time, temperature, and catalyst concentration were selected and the other two factors were fixed at levels defined based on the results of the previous stage. The selected variables were studied in different levels in the Doehlert design of experiments and it showed to be very efficient (because it demanded few experiments) to find the optimum conditions (within the experimental domain studied) for the transesterification of fodder radish crude oil.

High temperatures, together with high concentrations of the catalyst and/or extended reaction times, tended to reduce the ester content in the products of the transesterification reaction. One of the reasons for this observation may be that these conditions can promote the formation of unwanted products (such as soaps), due to the occurrence of reactions that compete with the transesterification.

The optimum synthesis conditions obtained within the researched experimental domain were: reaction time = 70 min, reaction temperature = 30 °C, catalyst concentration = 1.3% w/w, with a molar ratio of ethanol/oil = 6:1, and a stirrer speed of 500 rpm. A very high stirring speed (over 500 rpm) was disadvantageous for the efficiency ofthe reaction. In these conditions, the ester content in biodiesel was 97.9% w/w. This ester content and all the other physical chemistry properties are in conformity with Brazilian regulation for commercial biodiesel and are strong evidence that the synthesis of biodie-sel from fodder radish crude oil can be carried out efficiently in a single step.

5.3. Oilseed radish as a raw material for biogas production

In 2009, the EU began to develop policies to ensure a ‘sustainable energy union and long-term climate change policy’. As part of this project, the Renewable Energy Directive (RED) was created, which initially set a binding target of 20% of final energy consumption from renewable sources by 2020 (Kaletnik et al., 2020a,b; Tokarchuk et al., 2020). In Europe, as of 2022, 22% of the total primary energy supply comes from renewable sources. Of this share, more than half – 58% is biomass energy. In total, at the beginning of 2022, the European Union had 880 biomethane plants concentrated in 20 countries based on the use of biomass from various crops. The European Union plans to produce 35 billion cubic meters of biomethane by 2030 to replace 10% of conventional gas consumption. And by 2050, it wants to increase this share to 60 percent. The total potential for biomethane production in the world is 1.15 trillion cubic meters per year (EBA Statistical Report, 2023; Honcharuk et al., 2023 a, b). According to various estimates, 43–60% of this production potential is still generated from crop biomass (EBA Statistical Report, 2023).

At the same time, it is understood that achieving the noted potential and biogas production in terms of the use of biomass from specific crops requires a constant expansion of their range with a focus on the most adapted species with low resource capacity of their cultivation technologies for each country (Herrmann et al., 2016, 2016a; Komasilovs et al., 2021). Such monitoring is carried out on an ongoing basis, both from the point of view of in-depth study of traditional crops for biogas production in the total number of 25–30 species to the study of new crops, including wild species and even weeds (Zhang, 2021). Among these studied species, a group of cruciferous crops (spring and winter rape, white mustard, biomass waste from cabbage vegetable crops, and turnip) have proven to be effective candidates for biogas (biomethane) production both in the world and in Ukraine (Morozova, 2020; Jacob et al., 2021; Słomka & Oliveira, 2021; Gioulounta et al., 2023). At the same time, it is noted that a number of common crop species are not fully involved in the study of the efficiency and productivity of bomethane fermentation processes and the assessment of their possible and effective use in the system of alternative biofuel production (Molinuevo-Salces et al., 2013, 2013a; Zhang, 2021).

From this point of view, the classical oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers. (synonymously known as *Raphanus sativus* var. *oleifera* Metzg.)), a typical representative of the Cruciferous family with a wide range of adaptive properties and valuable biological traits, which is adapted to cultivation at different cultivation periods from early spring to late autumn with the possibility of full-species intermediate cultivation in crop rotations of different rotation (Tsytsiura, 2019, 2020a, 2021a,b, 2022a) is an attractive candidate for studying in the processes of biomethane production from its biomass. It is also noted that oilseed radish, from the point of view of forming a significant mass in a short period against the background of a wide range of adaptive properties and taking into account the appropriate levels of C/N ratio, can be considered as a potential candidate for the implementation of the goals of the green course and alternative bioenergy, since it combines the valuable properties of phytoremediation and phytomeliorant and the energy intensity of its biomass determined by the biomethanization process (Herrmann et al, 2014, 2016, 2016a; Hu et al., 2018; Qiao et al., 2018). At the same time, it should also be noted its importance as a green manure with intensive development of the root system, providing intensive soil drainage and replenishing the soil profile with a significant amount of organic matter against the background of the proven effect of anti-nematode activity and soil biofumigation (Rinnofner et al, 2008; Thiessen & EntzMartin, 2011; Jabnoun-Khiareddine et al., 2016; Hemayati et al., 2017; Jaskulska et al., 2017; Technical Note, 2020; Hansen et al., 2022). In addition, its positive effect on agrophysical properties and soil regimes, reduction of the level of total weeds under systematic cultivation as a predecessor and intermediate crop in crop rotations of different rotation intensities has been established (Lehrschb & Gallian, 2010; Chapagain et al., 2020; Tsytsiura, 2020b; Hudek et al., 2022). Its importance has also been proven from the point of view of using seed oil as a component of mixed biofuels (Ávila & Sodré, 2012; Chammoun et al., 2013; Faria et al., 2018; Tsytsiura, 2022b).

The noted agro-technological properties of oilseed radish can be attributed to a potential candidate for biomethane production, given that classical crops for biogas processing according to the basic principles of methane co-fermentation should be characterized by multifunctionality with the possibility of intermediate cultivation in crop rotation (MolinuevoSalcesi et al., 2014). In this regard, it is important to study such indicators as the net energy efficiency per hectare and biomass efficiency per hectare (m^3 CH_4 ha^{-1}) as important parameters for the application of intercrops as substrates in methane fermentation (Seppälä, 2013; Launay et al., 2022). Plant biomass, due to the high content of lignocellulosic substances, comprising mainly cellulose, hemicellulose, and lignin, requires pretreatment in order to improve susceptibility to biodegradation (Gioulounta et al., 2023). On the other hand, in recent years, interest in this crop has tended to grow, but its use as a component of bomethane production has focused on studying the efficiency of the cake after processing its seeds into oil for bomethane fermentation (Hu et al., 2018; Wendel et al., 2020; Junges et al., 2020). This significantly narrows its assessment in the areas of multi-purpose application directly in mobile biogas plants and stationary biofuel production directly within rural areas to ensure their bioenergy autonomy.

Taking into account the above-mentioned and the poorly studied biogas productivity of crude biomass of oil radish, the aim of the work was to investigate the biogas and methanogenic potential of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) and to estimate the biogas efficiency of its biomass.

This research (Tsytsiura, 2023a) was carried out in 2020–2022 at Vinnytsia National Agrarian University (49°11′ N, 28°22′ E), during the potentially possible oilseed radish growing season of April-September (178 days). Height above sea level: 325 m. The area has a temperate continental climate. During the study period, the maximum and minimum temperatures were 18.3 °C in July and 15.8 °C in May, respectively. Mean annual relative humidity was 77% and mean annual precipitation was 480–596 mm.

The soil cover of the research field was represented by gray forest soils (Luvic Greyic Phaeozem soils) (IUSS Working Group, 2015) of medium loamy texture (according to the State Standard of Ukraine (SSU) ISO 11277:2005). According to the results of the agrochemical survey of the soil and the determination of basic indicators in accordance with national standards, it had the following agrochemical parameters (for the period of crop rotation) humus 2.02–3.20% (according to SSU 4289:2004), mobile forms of nitrogen 67–92 mg kg^{-1} (according to SSU ISO 11261:2001), phosphorus 149–220 mg kg^{-1} (according to SSU 4115-2002) and potassium 92–126 mg kg^{-1} (according to SSU 4115-2002) with metabolic acidity of the soil solution (pH_{KCl}) 5.5–6.0 (according to SSU ISO 10390:2001).

The research was conducted using the variety 'Zhuravka', which is widespread in the region, using the method of pre-sowing design of its agrocenosis, which is used for the least costly variant of growing the crop in the research area with a sowing rate of 2.0 million seeds per ha using the conventional row method on an unfertilized background. The general scheme of the experiment with indexing options is presented in Table 5.31.

Table 5.31

Factors of the experiment of biomethane productivity of oilseed radish leaf mass with preliminary silage fermentation (at four times replication (total combinatorics N = 48) (Tsytsiura, 2023a)

Factor of sowing time	**Factor in the timing of leaf mass harvesting**	**Interaction of the factors**
A_1 (budding stage, BBCH 50–53)	B_1 (I)	A_1B_1, A_1B_2, A_1B_3, A_1B_4 A_2B_1, A_2B_2, A_2B_3, A_2B_4, A_3B_1, A_3B_2, A_3B_3, A_3B_4
A_2 (flowering stage, BBCH 64–67)	B_2 (II)	
A_3 (green pod stage, BBCH 73–75)	B_3 (III)	
	B_4 (IV)	

The sowing dates were as follows: first (I) (second decade of April – early spring), second (II) (first decade of May – spring), third (III) (third decade of May – late spring), fourth (IV) (second decade of June – summer).

The hydrothermal regime of the period preceding sowing and the period of active vegetation was estimated by the hydrothermal coefficient (HTC) according to equation (5.8):

$$ГТК=\frac{\sum R}{0.1\times\sum t_{>10}}, \tag{5.8}$$

where is the sum of precipitation (ΣR) in mm for the period with temperatures above 10 °C, the sum of effective temperatures (Σt>10) for the same period, reduced by a factor of 10. Ranking of HTC values (Evarte-Bundere and Evarts-Bunders, 2012): HTC > 1.6 – excessive humidity, HTC 1.3–1.6 – humid conditions, HTC 1.0–1.3 – moderately dry conditions, HTC 0.7–1.0 – dry conditions, HTC 0.4–0.7 – very dry conditions.

The analysis of weather conditions and the level of their variability for the period 2013–2022 was carried out on the basis of the coefficient of significance of deviations (C_{sd}) of the elements of the agrometeorological regime of each of the studied years from the average long-term one in accordance with Equation 5.9:

$$C_{sd}=\frac{\left(X_i-X_{av}\right)}{S}, \tag{5.9}$$

where: C_{sd} – coefficient of significance of deviations; current weather element; X_{av} – indicator of the long-term average (at least ten-year period); S – standard deviation; i – year number. C_{sd} level: 0 ÷ 1 – conditions are close to normal; 1 ÷ 2 – conditions differ significantly from the long-term average; > 2 – conditions are close to extreme.

According to the significance of deviations of the mean monthly value of the HTC from the average long-term data, the years of the study period by the value of Csd (Table 5.32, Figure 5.17) are classified as 2021 – dynamically variable with extremes of excessive moisture and extra-dry conditions, 2020 and 2022 – conditions close to typical for the long-term hydrothermal regime of the study area. The years of research in the order of increasing stress on the growth processes of oilseed radish plants from the standpoint of the dynamics of the amplitude of changes in average daily temperatures are as follows: 2022–2021–2020. The timing of leaf mass selection was set in accordance with the international scale of plant development BBSN (Growth stages of mono- and dicotyledonous plants) (Test Guidelines..., 2017), taking into account the possible achievable phenological stages of growth and flowering of oilseed radish plants, taking into account hydrothermal conditions in May-August, which are decisive in the levels of bioproductivity of this crop and are variably achievable at different sowing dates (Tsytsiura, 2019). Such phenostages of selection were the budding phase (BBCH 50–53), flowering (BBCH 64–67), and the beginning of the green pod (BBCH 73–75) (Figure 5.17–5.18).

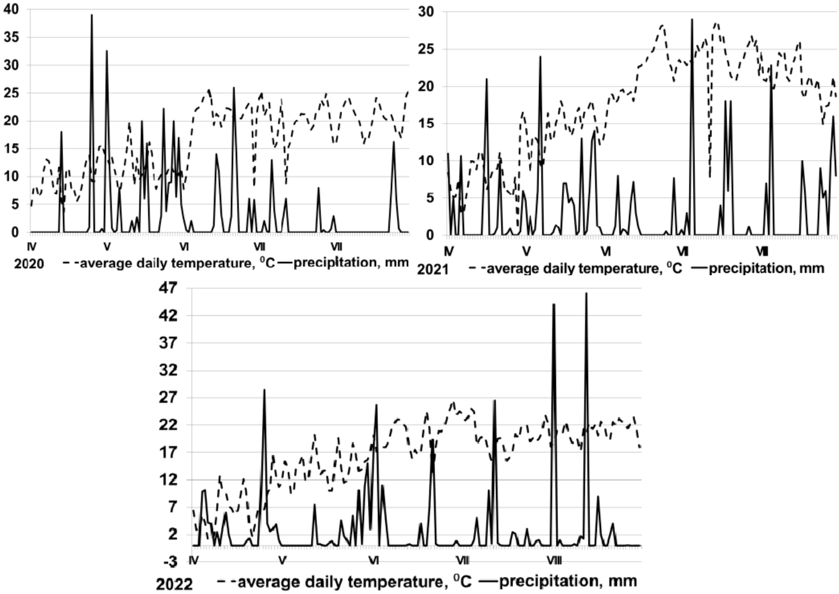


Figure 5.17 – Average daily temperature (°C) and precipitation (mm) during the active vegetation period of oilseed radish of different sowing dates (May–August)

In each phase of accounting, plants were cut at a height of 5 cm in the morning to minimize direct exposure to the sun on the tissues of cut plants and to maximize the preservation of turgor until shade drying and transported immediately to the laboratory for further analysis. Plant samples were collected from 1 m^2 plots at 4 randomly selected locations.

The characteristics of the plant mass were determined using a laboratory scale YP50002 (5 kg) with a discretion of 0.01 g. The resulting dried samples were re-weighed and ground using a Vilitek VLM-16 800 g 2200 mL electrostatic laboratory mill.

Table 5.32

Estimation of GTC values during the active vegetation period of oilseed radish, 2020–2022 (Tsytsiura, 2023a)

Year of study	Months of the growing season								On average for the period V–IX
	V		VI		VII		VIII		
	X_i	C_{sd}	X_i	C_{sd}	X_i	C_{sd}	X_i	C_{sd}	C_{sd}
2020	5.489	4.637	1.474	-5.683	0.649	-1.344	0.474	-0.468	-0.715
2021	0.530	-0.322	1.077	-6.080	1.589	-0.404	1.513	0.571	-1.559
2022	1.388	0.536	1.483	-5.674	0.854	-1.139	1.77	0.828	-1.362
X_{av} (2013–2022)	1.905		1.385		0.868		0.725		–
S (2020–2022)	2.236		0.193		0.435		0.770		–

The resulting biomass was divided into three types of analysis. The first involved its chemical analysis, the second – chemical analysis of oilseed radish silage obtained from its biomass at different sowing and harvesting dates, and the third – studying the dynamics of anaerobic digestion of oilseed radish silages (inoculum subtracted) depending on the options for its preparation by sowing and harvesting dates of the initial biomass.

Crop materials were chopped to a particle length of < 20–30 mm and preserved by ensiling. The laboratory silage process was carried out in 1.5-liter glass silos (J. WECK GmbH u. Co. KG, Wehr, Germany) immediately after grinding with pressing and full filling of the containers and subsequent hermetic sealing according to the methodology described in detail by Seale and Knap (2011), taking into account the methodology used in the studies of Herrmann et al. The closure system provided for the free release of gases generated during anaerobic fermentation. The temperature regime during 90 days of silage was constant at 25 °C ± 0.5. The silage was a single component without preservatives in quadruplicate for each experimental variant.

All laboratory chemical analyses applied to the obtained crushed samples of oilseed radish (moisture, ash, fat, protein and fibre content according to AOAC (2005) expressed on an absolutely dry weight basis) were carried out in quadruplicate in a specialized certified and accredited laboratory of Vinnytsia branch of the state institution 'Institute for Soil Protection of Ukraine' which is certified according to ISO 22000 international certification.

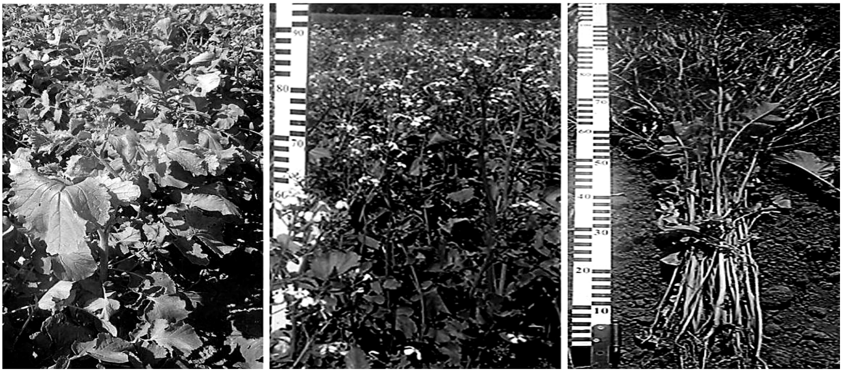


Figure 5.18 – General development of Zhuravka oilseed radish plants (from left to right) at the budding stage (BBCH 50–53), flowering stage (BBCH 64–67), and beginning of green pod (BBCH 73–75), 2021 (Tsytsiura, 2023a)

Crop materials of oilseed rape obtained from experimental plots of different sowing dates were wilted to a target DM content of 30–35% before the laboratory silage procedure (according to the recommendations of Herrmann et al. (2016)) before chopping and ensiling.

The obtained silage samples of different variants were subjected to low-temperature storage in a CRO/400/40 refrigerator (equipped with a temperature field control system) at 18 °C ± 0.5 after their removal from glass experimental silos according to the recommendation of Herrmann et al. (2016) before further processing for chemical composition analysis and biomethane production. The dry matter (DM) and organic dry matter (ODM) contents were measured by drying in an oven at 105 °C and then ashing the dried sample at 550 °C according to standard methods (AOAC, 2005). The dry matter content was adjusted to account for the loss of organic acids and alcohols during oven drying according to the recommendations of Herrmann et al. (2016).

The silage pH was determined using a high-precision combined pH electrode for continuous pH monitoring Sen Tix 41 (WTW, Weilheim, Germany, 2018 modification). Additional chemical components (lactic acid, volatile fatty acids, alcohols) were analyzed in cold silage extracts in the certified and accredited laboratory of the quality of crop products of Vinnitsa Oil Seeds Crushing Factory (private joint stock company). In particular, lactic acid was analyzed using a liquid chromatograph HPLC-1100 BIOEVOPEAK, taking into account the methodological recommendations of Xiao-song (2012) and Herrmann et al. (2016).

The analysis of volatile fatty acids (acetic, propionic, n-butyric, iso-butyric, n-valeric, iso-valeric, and n-caproic) and alcohols (ethanol, propanol, 1,2-propanediol, 2,3-butanediol) was performed using a Shimadzu GC-2014 gas chromatograph (modified with a capillary column and flame ionization detector) (Shimadzu Corporation, Japan).

Crude fat and crude fiber were determined according to the guidelines of Herrmann et al. (2014, 2016, 2016a) using standard laboratory methods (SSU (State standard of Ukraine) 8844:2019, SSU 8128:2015, SSU ISO 16472:2013, SSU ISO 7982:2015).

The elemental nitrogen content (Total Kjeldahl Nitrogen (TKN)) analysis of dry soil biomass was performed using the KjeLROC Kd-310 analyzer (ISO 17025) (in accordance with the State standard of Ukraine ISO 5983:2003, 2003 and SSU (State standard of Ukraine) 8108:2015). The content of total organic carbon (TOC) in the dry weight of plants after mechanical grinding was determined using a laboratory analyzer of total organic carbon of the TOC-LCPH series according to the standard protocol for low-temperature thermocatalytic oxidation of plant material.

Crude protein was calculated as the elemental nitrogen content multiplied by the standard conversion factor of 6.25, which is accepted with certain reservations for fresh and silage biomass of a whole group of crops of different species and families (Sáez-Plaza et al., 2013). The C/N ratio in silages was calculated as the ratio of elemental carbon to elemental nitrogen to assess the intensification of anaerobic digestion. Nitrogen-free extracts (NfE) were calculated as the difference between the content of 100% dry matter and the corresponding content of crude protein, crude fiber, crude fat and crude ash.

The assessment of the potential methane yield from laboratory silage samples with the determination of general parameters of its quality was investigated during anaerobic fermentation according to the general methodology proposed by Herrmann et al. (2016a) and Tang et al. (2020). For anaerobic fermentation, we used 1.0-liter glass vessels filled with 0.75 liters of inoculum and such an amount of plant material that the ratio of ODMS substrate to ODM inoculum was 0.5, taking into account the recommendations of Field et al. (1988) and Satyanarayana et al. (2008). Further actions to prepare the substrate for anaerobic digestion were carried out in accordance with the guidelines of Carvalho et al. (2011), which provided for bringing the final volume of the vessel to 700 mL with distilled water and normalizing the pH of the inoculum medium and silage substrate in the resulting mixture (based on the studies of Jayaraj et al. (2014) and Putra et al. (2023)) to 7.0–7.2 by corrective addition (if necessary, according to the preliminary control determination) of a 10M NaOH solution. As a control, a reactor containing only inoculum was used in order to discount that volume from the final volume of experimental variants. Anaerobic conditions in the laboratory reactors were created by flushing with nitrogen for 2/3 minutes immediately before closing the reactor.

Digestive enzyme obtained as a result of fermentation of pig manure for 14 days and obtained from the commercial enterprise 'Organic-D', which has a well-established biogas fermentation system of the European level of certification, was used as an inoculant. The resulting subtrate called 'Efluent' is certified in 2018 (Technical conditions of Ukraine 20.1-38731462-001:2018) and patented in Ukraine (Kaletnik et al., 2022 b; Lohosha et al., 2023). Based on the analysis in the Prime Lab Tech laboratory (according to the ISO 22000 international certification), this digestate had the following average chemical characteristics and standard deviation: pH 8.2 ± 0.3; DM 2.5 ± 0.7%; TDS 62.7 ± 3.3% of DM; N 2.9 ± 1.2 g kg^{-1} ; NH_4–N 2.3 ± 0.7 g kg^{-1}; organic acids 1.7 ± 0.5 g kg^{-1}). The vessels were placed in a water bath with a constant temperature of 35 °C ± 0.5 with prolonged incubation for 60 days. Active shaking of the vessels was performed once a day at the same time. The biogas generated during the incubation period was collected in wet gas meters and recorded using a standard procedure for displacement of acidified saturated barrier solution with NaCl (VDI, 2006). The biogas volume was determined daily, corrected for the volume of biogas produced by the inoculum without substrate and normalized to standard conditions (dry gas, 0 °C, 1013 hPa). For this correction, the inoculum without substrate was subjected to the same anaerobic digestion procedure and used in the analysis of biogas production kinetics as a correction basis (according to Herrmann et al., 2016). Biogas composition for methane content was measured using a portable gas analyzer equipped with infrared sensors (HONEYWELL BW Flex, USA). The specific methane yield was calculated as the sum of methane produced during the test period per ODM of the silage sample in the corresponding experimental variant.

Kinetic analysis to determine the rate of biodegradation of silage samples during anaerobic digestion. For this purpose, standardized approaches were applied using the first-order differential equation (equation (3)) and the modified Gompertz equation (equation (5.10)) with fitting to the cumulative methane production curves (Lay et al, 1997 Mittweg et al., 2012) obtained during anaerobic digestion tests using the CurveExpert Professional v. 2.7.3 software package (Hyams Development) and Matlab R2016a software (TheMathWorks Inc., Natick, MA, USA).

$$y(t) = y_m\left(1 - e^{(-k_1 t)}\right), \tag{5.10}$$

where, y(t) is the cumulative specific methane yield at time *t* (L_N $kg^{-1}{}_{ODM}$), y_m is the maximum specific methane yield at theoretically infinite digestion time (L_N $kg^{-1}{}_{ODM}$), *t* is the time (days) and *k* is the first order decay constant (day^{-1}).

$y(t) = y_m \exp\left[-\exp\left(\frac{Rm^e}{y_m}(\lambda - t) + 1\right)\right]$ (after the transformation by logarithmization:

$$R_m = \frac{y(t)\left[In\left(In\frac{y(t)}{y_m}\right) - 1\right]}{e\left[\lambda - t\right]} \tag{5.11}$$

where, y(t) is the cumulative specific methane yield at time *t* (L_N $kg^{-1}{}_{ODM}$), y_m is the maximum specific methane yield at theoretically infinite digestion time (L_N $kg^{-1}{}_{ODM}$), R_m is the maximum specific methane production rate (L_N $kg^{-1}{}_{ODM}$ day^{-1}), *t* is the time (days) and *λ* is the lag phase (days), e = Euler's constant.

The lag period (λ) was defined as the period from the beginning of the anaerobic digestion test to the onset of methane emission, recorded in hours and subsequently converted to days with a conversion to a day length of 24 hours with the onset of gas emission recorded (based on the recommendations of Kim and Kim (2020)) using the MQ-4 methane gas sensor with the Arduino AVR Pic board.

The half-life (t_{50}) was determined based on the interpretation of the modified Gompertz equations as the time when 50% of the maximum specific methane yield is reached (days).

The degree of integrated connection of the biochemical composition of oilseed radish silage biomass with the main indicators of the kinetics of the productive process of biomethane production was estimated by the value of the coefficient of determination of the connection (Equation 5.12) and the use of the method of weighting the correlation graph in two interpretations according to Equations 5.13 and 5.14:

$$d_{yx} = r_i j^2 \times 100 \tag{5.12}$$

$$G = \sum_{|r_{ij}| \geq \alpha} |r_{ij}| \tag{5.13}$$

where r_{ij} is the correlation coefficient between the i-th and j-th indicator. Only reliable correlation coefficients were used in the calculation.

$$G' = \left(\sum_{|r_{ij}| \geq \alpha} |r_{ij}|\right) / n \tag{5.14}$$

n is the number of statistically significant correlation coefficients.

Statistical analysis of research results. It was conducted using Past 4.13 software (Øyvind Hammer, Norway) with the calculation of Pearson's correlation coefficients and multiple regression analysis according to the standard procedure (Wong, 2018). To compare the regression models, we used the coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), and relative root mean square error (RRMSE).

The data obtained were analysed using analysis of variance (ANOVA) with determination of the share of influence of factors in the dispersion scheme. Tukey's HSD test in R (version R statistic i386 3.5.3) with multiple comparisons of the parameter means at the 99.9%, 99% and 95% family-wise confidence levels were used. In evaluating the obtained array of multiple values, standard indicators were used for analysing variable data (multi-year and genotypic components: $\bar{x}$ – average, SD – standard deviation, C_v – coefficient of variation).

According to Herout et al. (2011) and Ahlberg and Nilsson (2015), the assessment of the potential of a particular crop for biogas production should necessarily include an assessment of both its bioproductivity in terms of the formation of an appropriate level of biomass yield and a general assessment according to the generally accepted chemical analysis structure. Taking into account these indicators allows us to draw a conclusion about the bioenergy potential of the species and the feasibility of its cultivation for biogas production. Evaluation of different sowing dates of oilseed radish, which are traditionally practiced in relation to this crop in the research area, proved a relatively high level of its bioproductivity both in early spring and summer with significant differences between the variants (Table 5.33).

Taking into account the findings on the comparable productivity of cruciferous crops for multiple uses (Maier et al., 2017; Sánchez et al., 2023), oilseed radish can be attributed to crops with high productive potential in terms of agrobiomass yield both in total weight and dry matter. There is also a steady tendency to decrease the level of biomass yield with a shift in the sowing dates of the crop.

Thus, the overall decrease in biomass yield with a sequential shift in sowing dates compared to the most productive first term was 12.41%, 39.97%, 51.23%, respectively, for the second to fourth applied terms. In terms of biomass yield in terms of dry matter, similar indicators amounted to 11.21%, 33.19% and 47.94%, respectively. The resulting factor of this trend is the change in hydrothermal conditions that develop during the period of active growth of vegetative mass for each sowing date with a certain nature of dependence in the form of regression equations (Table 5.34).

According to these equations, the efficiency of oilseed radish bioproductivity in terms of biomass yield depends on the ratio of precipitation and the increase in average daily temperatures. Taking into account the dimensionality of the regression analysis coefficients, the optimum for oilseed radish implies two main models of effective vegetation – sufficient moisture supply with a moderate rate of increase in average daily temperatures and a moderate moisture regime against the background of a stable temperature regime close to the optimum of physiological processes for cruciferous plants. Due to this nature, oilseed radish should be attributed to crops with optimal productivity, and therefore optimal regions of biogas application, belong to temperate regions with precipitation in May–July at the level of 220–250 mm and average daily temperature for the same period in the range of 16–18 ºC.

Table 5.33

Oilseed radish biomass yield depending on the sowing date (average for 2020–2022), t ha^{-1} ($\bar{x}$± SD) (Tsytsiura, 2023a)

Sowing date	Phenological stages					
	budding stage (BBCH 50–53)		flowering stage (BBCH 64–67)		green pod stage (BBCH 73–75)	
	1	2	1	2	1	1
I	9.18 ± 1.15	0.93 ± 0.10	17.29 ± 2.62	2.18 ± 0.33	24.77 ± 3.18	3.67 ± 0.45
II	8.11 ± 1.42	0.80 ± 0.14	15.17 ± 2.08	1.85 ± 0.22	21.60 ± 2.78	3.37 ± 0.38
III	6.59 ± 1.40	0.71 ± 0.16	11.70 ± 2.73	1.62 ± 0.32	12.47 ± 3.50	2.20 ± 0.53
IV	5.87 ± 1.59	0.54 ±. 0.15	8.55 ± 3.11	1.28 ± 0.34	10.57 ± 2.90	1.71 ± 0.40
Tukey's test (R_{min} for p_{adj} < 0.05)	0.23–0.57	0.07–0.11	0.85–1.57	0.12–0.21	1.09–1.78	0.18–0.27

1 – in raw weight, t ha^{-1}; 2 – in dry matter (DM), t ha^{-1}.

Compensation for the negative effect of high average daily temperatures for oilseed radish according to the ratio of the coefficients of the regression equations (X_1/X_2 = 28–49) and taking into account the study (Ahmad, 2017) is possible in the case of intensive moisture at the level of 300–350 mm for the period May–July (with a decrease in the ratio between the coefficients of the regression equation to the level of X_1/X_2 = 20–28).

The chemical analysis of oilseed radish leaf mass also had significant differences with changes in the timing of sowing of oilseed radish (Table 5.35). The analysis of the presented indicators made it possible to estimate the rate of the so-called physiological aging of oilseed radish plants and the consideration of this factor in the suitability of its biomass for biogas production both in terms of changes in phenological phase s and changes in sowing dates. Comparing the phenological phase s of budding and green pod for the average sowing time, it was found that there was a steady tendency to decrease the content of crude protein by 37.52% and crude ash by 32.09%, increase the content of crude fat by 6.20%, crude fiber by 49.33%, with a relatively stable NfE (increase by 1.89%).

Table 5.34

Regression dependences of oilseed radish biomass yield on hydrothermal conditions of the growing season in a single-model comparison of different sowing dates (in the total data set for 2020–2022 (N = 48)) (Tsytsiura, 2023a)

The yield of of leaf and stem mass (Y), t ha^{-1}	Interphase period 'seedlings–flowering'
	$Y = 44.939 - 1.680X_1 + 0.059X_2$ ($R_{мн} = 0.753$. $R^2_{adj} = 0.517$. $p = 0.0007...0.004^*$)
	Interphase period 'seedling–green pod'
	$Y = 72.523 - 2.926X_1 + 0.0634X_2$ ($R_{мн} = 0.754$. $R^2_{adj} = 0.518$. $p = 0.001...0.004^*$)
Dry matter yield (Y_1), t ha^{-1}	Interphase period 'seedlings–flowering'
	$Y_1 = 5.550 - 0.196X_1 + 0.004X_2$ ($R_{мн} = 0.730$. $R^2_{adj} = 0.477$. $p = 0.0001...0.048^*$)
	Interphase period 'seedling–green pod'
	$Y_1 = 10.077 - 0.388X_1 + 0.006X_2$ ($R_{мн} = 0.700$. $R^2_{adj} = 0.428$. $p = 0.0009...0.039^*$)

Notes: 1. Climatic factors for the corresponding interphase periods of vegetation: X_1 – average daily air temperature, ºC; X_2 – precipitation, mm; 2. R_{mn} – multiple correlation coefficient, R^2_{adj} – adjusted coefficient of determination, * – actual p-level interval for the coefficients of the equation (at a minimum significance level of $p<0.05$).

At the same time, due to an increase in the content of total organic carbon by 7.96% against the background of an adequate decrease in the content of crude protein, the C/N ratio increased by 1.72 times. Certain regularities were also noted for the shift in sowing dates in the fourth-first comparison within the accounting phenological phases. For the budding phase, there was an increase in crude protein (and elemental nitrogen (TKN)) by 22.56%, organic carbon by 0.34%, and a decrease in the C/N ratio by 13.97%. For other side, the content of crude fat, crude fiber and crude ash increased by 37.60%, 24.68% and 34.22%, respectively, with a decrease in NfE by 23.48%. For the flowering phase, in the same variant of comparing the first and fourth terms, an increase in elemental nitrogen (TKN) by 6.76%, organic carbon by 1.64% with a decrease in the C/N ratio by 3.79% was noted.

Table 5.35

Chemical composition of oilseed radish leaf mass by stages of growth and development depending on the sowing date and phenological phase of plants (average for 2020–2022) (Tsytsiura, 2023a)

Sowing date	Crude protein (CP) ($\%_{DM}$)			Crude fat (CF) ($\%_{DM}$)			Crude fibre (CFb) ($\%_{DM}$)			Crude ash (CA) ($\%_{DM}$)			NfE ($\%_{DM}$)		
	$\bar{x}$	SD*	C_v**	$\bar{x}$	SD	C_v	$\bar{x}$	SD	C_v	$\bar{x}$	SD	C_v	$\bar{x}$	SD	C_v
budding stage (BBCH 50–53)															
I	13.12	2.40	18.29	2.58	0.53	20.54	17.22	3.83	22.24	13.12	1.12	8.54	53.96	4.76	8.82
II	14.13^{c}	2.17	15.36	2.22^{c}	0.46	20.73	25.14^{a}	5.11	20.33	13.24^{d}	1.89	14.27	45.40^{b}	4.69	10.33
III	19.27^{a}	2.61	13.54	2.14^{c}	0.52	24.30	21.52^{b}	4.72	21.93	18.07^{a}	3.90	21.58	39.00^{a}	5.44	13.95
IV	16.08^{b}	0.94	5.85	3.55^{b}	0.77	21.69	21.47^{b}	2.58	12.02	17.61^{a}	4.41	25.04	41.29^{a}	6.12	14.82
flowering stage (BBCH 64–67)															
I	13.89	1.11	7.99	3.04	0.27	8.88	21.77	4.62	21.22	12.58	2.55	20.27	48.72	4.56	9.36
II	13.63^{d}	0.62	4.55	2.73^{c}	0.32	11.72	26.91^{a}	5.89	21.89	12.53^{d}	1.42	11.33	44.20^{c}	4.71	10.66
III	17.48^{a}	1.65	9.44	2.75^{c}	0.52	18.91	23.12^{c}	5.34	23.10	14.17^{b}	2.83	19.97	42.48^{b}	7.38	17.37
IV	14.23^{c}	1.03	7.24	2.52^{c}	0.71	28.17	24.78^{c}	1.72	6.94	14.54^{b}	3.08	21.18	43.93^{c}	3.25	7.40
green pod stage (BBCH 73–75)															
I	8.08	1.12	13.86	3.14	0.98	31.21	32.31	6.73	20.83	8.39	0.68	8.10	48.08	8.18	17.01
II	8.92^{c}	1.66	18.61	3.61^{c}	0.78	21.61	32.34^{d}	7.13	22.05	9.04^{c}	1.99	22.01	46.09^{c}	2.35	5.10
III	11.44^{b}	2.85	24.91	2.04^{b}	0.20	9.80	31.88^{c}	5.27	16.53	11.27^{a}	1.32	11.71	43.37^{b}	3.29	7.59
IV	10.67^{b}	4.35	40.77	2.35^{b}	0.65	27.66	30.92^{b}	5.34	17.27	10.55^{b}	2.46	23.32	45.51^{b}	5.59	12.28

(End of Table 5.35)

Sowing date	Total Kjeldahl Nitrogen (TKN) ($\%_{DM}$)			Total organic carbon (TOC) ($\%_{DM}$)			Ratio C/N	
	$\bar{x}$	SD*	R_V***	$\bar{x}$	SD	R_V	$\bar{x}$	R_V
budding stage (BBCH 50–53)								
I	2.10	0.38	1.72–2.48	37.47	2.08	35.39–39.55	17.84	15.95–20.60
II	2.26^{c}	0.35	1.91–2.61	38.12^{b}	2.29	35.83–40.41	16.87^{b}	15.48–20.33
III	3.08^{a}	0.42	2.67–3.50	37.63^{c}	2.82	34.81–40.45	12.22^{a}	11.56–13.04
IV	2.57^{b}	0.15	2.42–2.72	37.17^{b}	3.09	34.08–40.26	14.46^{a}	14.08–14.80
flowering stage (BBCH 64–67)								
I	2.22	0.18	2.04–2.40	38.67	3.57	35.10–42.24	17.42	17.21–17.60
II	2.18^{d}	0.10	2.08–2.28	40.04^{a}	3.89	36.15–43.93	18.37^{b}	17.38–19.27
III	2.80^{a}	0.26	2.53–3.06	39.14^{b}	4.28	34.86–43.42	13.98^{a}	13.78–14.19
IV	2.28^{c}	0.16	2.11–2.44	39.37^{b}	4.63	34.74–44.00	17.27^{c}	16.46–18.03
green pod stage (BBCH 73–75)								
I	1.29	0.18	1.11–1.47	41.03	3.89	37.14–44.92	31.81	30.55–33.45
II	1.43^{c}	0.27	1.16–1.69	40.92^{c}	4.17	36.75–45.09	28.62^{a}	26.69–31.68
III	1.83^{b}	0.46	1.37–2.29	40.38^{b}	4.55	35.83–44.93	22.07^{a}	19.63–26.15
IV	1.71^{b}	0.70	1.01–2.40	40.03^{b}	5.02	35.01–45.05	23.41^{a}	18.78–34.66

*SD – standard deviation; **C_v – coefficient of variation, R_V – range of values. Significance levels in comparison to the first (I) sowing term: a – 0.1%; b – 1%; c – 5%; d – no significant difference.

The crude fat content decreased by 17.11%, while the crude fiber and crude ash content increased by 13.83% and 15.88%, respectively, with a decrease in NfE by 9.83%. For the green pod phase, the elemental nitrogen and organic carbon content increased by 6.76% and 1.64%, respectively, with a decrease in the C/N ratio by 3.79%. Under the same conditions, crude fat, crude fiber, crude ash and NfE content decreased by 22.85%, 1.48%, 6.54% and 0.71%, respectively. According to the generalizations of Heiermann et al. (2009), Al Seadi et al. (2013), Tauš et al. (2020) and the presented data, the leaf mass of oilseed radish should be attributed to plants of potential candidates for biogas production through anaerobic digestion, with the optimum phenological phase use corresponding to the flowering phase of oilseed radish. It is for this phase that the necessary balance between the accumulation of fiber, nitrogenous compounds and nitrogen-free extractives has been established against the background of a variable hydrothermal regime. Such conclusions are also confirmed in the studies of Carvalho et al. (2011) and Molinuevo-Salces et al. (2013).

In the study by Herrmann et al. (2016), the period of possible biogas application of oilseed radish leaf mass covers the interval of BBCH 51–69 (end of budding and beginning of flowering phases). According to Belle et al. (2015), this phenological period also covers the beginning of fruit formation of oilseed radish plants, provided that it is combined with various wastes and manure.

The possibility of optimizing the suitability of plant biomass for anaerobic fermentation with methane production by preliminary silage has been investigated (Kreuger et al., 2011; López-Aguilar et al., 2023), which is most relevant for crops with a low C/N ratio and low dry organic matter content (Opurum, 2021; Hülsemann et al., 2023). Similar conclusions were confirmed in our research by applying the preliminary process of anaerobic silage fermentation to the options for harvesting oilseed radish leaf mass (Table 5.36).

It should be noted that previous studies (Ammann et al., 2009; Villalobos & Brummer, 2013; Zhou et al., 2021; Sánchez et al, 2023) emphasizes the value of oilseed radish as a silage crop during the phenological period of budding–flowering, but most researchers noted that due to the high moisture content of the mass and low values of the sugar minimum, its silage is difficult in a single-species composition, so preference should be given to combined silage of oilseed radish with cereals, cereal-legume mixtures and straw. Silage of oilseed radish in its pure form did not contribute to the long-term (traditional period of 4-6 months) preservation of the preserved mass before use. Depressurization of the silage mass at the beginning of its feeding led to a rapid deterioration in the quality of silage and a significant deterioration in its combinability. The appearance of a sharp unpleasant odor and rapid oxidation with blackening of the leaf-stem chopped mass was also characteristic of pure oilseed radish silage. It is for these reasons that the silage mass of oilseed radish can be considered as one of the components of biogas production, as emphasized in the studies of Carvalho et al. (2011), Molinuevo-Salces et al. (2013a) and Herrmann et al. (2016). The analysis of the chemical composition of silage mass of different terms and phases confirmed the technological reservations regarding the silageability of oilseed radish. Based on the level of alcohols and a number of acids (i-butyric, butyric, i-valeric, valeric and caproic acid) in the silage-fermented mass, a gradual increase in chemical stability and quality of silage was noted in the green pod phase. Thus, the concentration of these acids, when comparing the average time between the flowering and green pod phases, decreases by 2.58 times in favor of the latter phenological phase . A similar decrease with an index of 2.03 was observed for the concentration of alcohols in the silage mass. At the same time, the total acidity of the mass decreases by 0.4–0.6 pH units due to an adequate decrease in the content of a number of acids (lactic, acetic and propionic).

This dynamics is maintained with a similar character in the comparison of the first to the fourth sowing term). At the same time, the ratio of these acids (based on the studies of Rezende et al., 2015; Raboanatahiry et al., 2021; Chen et al., 2023; Wang et al., 2023) indicates a normal course of lactic acid fermentation and good preservation of leaf mass. Such features of biochemical changes are associated with the fact that in the fruiting phase (from the beginning of intensive green pod formation), the green mass of oilseed radish undergoes significant biochemical transformations, which opens up opportunities for independent silage of the leaf-stem mass of oilseed radish, due to a decrease in the buffering capacity of cell sap due to a decrease in the content of protein substances (Table 5.36) in plants during the approach and course of the generative phases of growth and development.

Table 5.36

Dry matter, organic dry matter and chemical parameters of silage fermentation of oilseed radish depending on the sowing date and phenological stage of plants (average for 2020–2022) (Tsytsiura, 2023a)

Sowing date	Dry matter (DM), %		Organic dry matter (ODM) ($\%_{DM}$)		Crude protein (CP) ($\%_{DM}$)		Crude fat (CF) ($\%_{DM}$)		Crude fibre (CFb) ($\%_{DM}$)		Crude ash (CA) ($\%_{DM}$)		Ratio C/N	
	$\bar{x}$	SD*	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
budding stage (BBCH 50–53)														
I	11.51	1.17	73.62	0.21	11.92	0.23	2.89	0.15	18.27	0.21	14.63	0.14	18,42	0.18
II	10.84^{b}	1.56	73.84^{d}	0.33	12.87^{b}	0.25	2.42^{c}	0.17	26.27^{a}	0.15	14.55^{d}	0.18	17,96^{c}	0.22
III	11.92^{c}	1.41	74.41^{b}	0.27	17.54^{a}	0.65	2.51^{c}	0.25	22.81^{a}	0.17	19.52^{a}	0.23	12,63^{a}	0.36
IV	9.93^{b}	1.74	72.92^{b}	0.25	14.68^{a}	0.36	3.79^{b}	0.18	22.59^{a}	0.09	18.69^{a}	0.27	14,85^{a}	0.29
flowering stage (BBCH 64–67)														
I	13.82	1.08	82.57	0.18	12.55	0.15	3.41	0.17	22.93	0.18	13.74	0.28	18,39	0.23
II	14.55^{b}	0.93	83.24^{c}	0.15	12.37^{c}	0.25	3.18^{c}	0.19	28.17^{a}	0.23	13.92^{c}	0.13	19,57^{b}	0.29
III	15.52^{a}	2.29	83.78^{b}	0.11	16.47^{a}	0.42	3.22^{c}	0.29	25.24^{a}	0.27	15.79^{b}	0.26	14,38^{a}	0.31
IV	12.74^{b}	1.57	81.77^{b}	0.22	13.11^{b}	0.64	2.97^{b}	0.45	26.51^{a}	0.10	15.84^{b}	0.30	18,24^{a}	0.38
green pod stage (BBCH 73–75)														
I	16.85	2.14	88.27	0.12	7.04	0.69	3.61	0.42	33.27	0.22	10.17	0.12	34,37	0.38
II	17.73^{b}	1.89	86.55^{b}	0.15	7.49^{c}	0.41	3.97^{c}	0.26	34.11^{c}	0.27	10.88^{c}	0.30	32,64^{b}	0.41
III	16.17^{c}	1.74	85.17^{a}	0.17	10.22^{a}	0.25	2.58^{b}	0.12	32.91^{c}	0.17	12.51^{a}	0.14	24,19^{a}	0.27
IV	15.72^{b}	2.27	84.38^{a}	0.11	9.58^{a}	0.55	2.92^{c}	0.36	32.29^{c}	0.19	12.08^{a}	0.37	25,27^{a}	0.30

(End of Table 5.36)

Sowing date	Sum of i-butyric, butyric, i-valeric, valeric and caproic acid ($\%_{DM}$)		Sum of ethanol, propanol, 1,2-butanediol, 2,3-propanediol ($\%_{DM}$)		pH		Lactic acid ($\%_{DM}$)		Sum of acetic and propionic acid ($\%_{DM}$)	
	$\bar{x}$	SD*	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
budding stage (BBCH 50–53)										
I	0.73	0.05	0.88	0.03	4.4	0.1	10.31	0.12	3.60	0.09
II	0.84^{c}	0.09	0.98^{c}	0.05	4.2^{c}	0.1	11.12^{b}	0.14	3.82^{c}	0.07
III	0.62^{c}	0.09	0.67^{b}	0.08	4.1^{c}	0.0	10.09^{c}	0.18	2.74^{b}	0.10
IV	0.96^{b}	0.11	1.12^{a}	0.07	4.2^{c}	0.3	11.74^{b}	0.11	3.55^{d}	0.08
flowering stage (BBCH 64–67)										
I	0.54	0.07	0.69	0.03	4.6	0.1	9.51	0.18	3.11	0.10
II	0.47^{d}	0.05	0.58^{c}	0.05	4.6^{d}	0.0	8.07^{a}	0.14	2.71^{b}	0.12
III	0.41^{c}	0.14	0.55^{b}	0.07	4.8^{b}	0.0	7.11^{a}	0.16	2.24^{b}	0.07
IV	0.72^{b}	0.09	0.78^{c}	0.09	4.5^{c}	0.2	9.98^{c}	0.09	2.92^{c}	0.07
green pod stage (BBCH 73–75)										
I	0.29	0.09	0.47	0.05	4.8	0.1	6.92	0.10	2.34	0.05
II	0.11^{a}	0.08	0.32^{b}	0.05	5.0^{b}	0.2	6.45^{c}	0.08	2.17^{c}	0.05
III	0.38^{c}	0.05	0.45^{d}	0.07	4.8^{d}	0.2	7.09^{c}	0.07	2.07^{c}	0.08
IV	0.44^{b}	0.12	0.56^{c}	0.11	4.7^{c}	0.1	7.55^{c}	0.12	2.39^{d}	0.03

* SD – standard deviation; Significance levels in comparison to the first (I) sowing date: a – 0.1%; b – 1%; c – 5%; d – no significant difference.

Due to these biochemical transformations in the anaerobic process of silage fermentation, natural changes in the properties of all potential plant species occur (Herrmann et al. (2016): decrease in protein content against the background of an increase in crude fat, fiber and ash content. The well-known process of compaction of the chemical formula of the mass during anaerobic silage is also characteristic of cruciferous plant species (Borreani et al., 2018; Serhat et al., 2022). Due to the identified features, the stability of silage mass preservation of oilseed radish increased consistently from silage samples collected in the budding phase to the same samples collected in the green pod phase. The system of shifting the sowing dates from early spring (I) to summer (IV) changes this stability by creating conditions for active fermentation with the formation of a larger proportion of organic acids (an increase of 9.87% in the systems of the first to fourth sowing date) as a result of slow anaerobic decay processes. Such processes, according to studies (Satyanarayana et al., 2008; Kim and Kim, 2020; Tang et al., 2020; Opurum, 2021), indicate an increase in the share of associated gases in the total composition of biogas, in particular the share of hydrogen sulfide, nitrite derivatives, which ultimately leads to a predicted shortening of the lag period of the anaerobic fermentation process (López-Aguilar et al, 2023) and also leads to a general reduction in the duration of the period with biomethane release in the interval of the overall anaerobic fermentation process (Kalyuzhnyi et al., 2009; Kintl et al., 2022). That is, taking into account the chemical composition of oilseed radish silos of different studied variants, a more intensive biomethane production process with a greater variable component at the points of daily fixation should be expected with an increase in the proportion of fermentation associated gases for the mass harvested during the budding phase of later sowing dates. Gradually, with the physiological aging of oilseed radish plants, with the achievement of the flowering phase and the green pod phase, the process of biogas production will have a longer fixation interval, a more pronounced lag phase, with a decrease in the variability of the gas structure in the total volume of biogas productivity at the corresponding fixation dates. These features, taking into account the chemical composition of oilseed radish silage, are based on the conclusions of a number of studies (Mähnert et al., 2005; Abu-Dahrieh et al., 2011; Rodriguez et al., 2017; Darimani and Pant, 2020; Beausang et al., 2021; Jauhiainen, 2022; Szwarc et al., 2022).

Attention should also be paid to such a criterion as the C/N ratio, which, according to many researchers, determines the intensity of the biogas anaerobic fermentation process. The C/N ratios of cover crops generally vary from 9 to 40 (Zheng et al., 2004; Justes et al., 2012; Ma et al., 2018; Hansen et al. 2021; Yang et al., 2022). The optimal C/N ratio for anaerobic degradation depends on the substrate used, but a value between 20–30 is recommended (Kwietniewska et al., 2014; Wang et al., 2015). When a substrate has low C/N ratios, it is considered to contain relatively high ammonium concentrations, inhibiting microbial growth and anaerobic digestion (Cerón-Vivas et al. (2019); Choi et al., 2020). According to Choi et al. (2020), carbon to nitrogen (C/N ratio) has effects on methane production yield and it is a very important factor for stable operation. When the C/N ratio is too high, biogas yield does not show the optimum due to acidogenic bacteria rapidly consuming nitrogen compared to methanogenic bacteria. When the C/N ratio is too low, most microbes rapidly consume nitrogen for growth. Although this has a positive effect on methane production rate. However, the lack of carbon type causes that decrease in acid formation, nitrogen accumulates in the form of ammonium ions (NH_4) that increase the pH (Yen & Brune, 2007) which adversely affects biogas production. At the same time, despite the established optimal C/N interval (20–30), it is emphasized (Guarino et al., 2016) that this indicator has certain species-specific reservations based on the chemical characteristics of a particular agrobiomass and biogas production technology. Thus, according to the conclusions of the same Guarino et al. (2016), depending on the mode of biogas production, this interval had wider limits from 9 to 50, and in the studies of Dębowski et al. (2022) and Manyi-Loh et al. (2023), the optimal value of this ratio had a complex complementary nature of interaction and biomethane productivity of the anaerobic digestion substrate in the range from 10 to 30. Similar conclusions regarding the specificity of the formation of the C/N ratio were made in these studies. Thus, for fresh leaf mass (Table 5), the C/N ratio was in the range of 12.22-31.81 and had a steady upward trend as the plants aged phenologically. Thus, averaged over the sowing dates for the budding phase, this indicator was 15.35. At the flowering and green pod stages, it was at the level of 16.76 and 26.48, respectively. In view of the established optimal interval of 20-30 with a possible species deviation of 10-30 and the available value of the standard deviation in the assessment of annual variation, oilseed radish should be attributed to crops with a suitable capacitive ratio of biochemical composition, which determines a certain potential for biogas yield. Given that the first and second sowing dates have a long-term average of above 30 for the green pod phase, the optimal predicted period of use of crude plant biomass without preliminary silage fermentation is in the range of phenological development of the BBSN 64-70. On the other hand, this level of C/N ratio allowed us to note the value of oilseed radish leaf mass for green manure (green organic fertilizer), which is especially valuable, given a number of studies (Li et al., 2019; Liu et al., 2020; Hansen et al., 2021; Wang et al., 2021), when used in the budding-flowering phase of BBCH 50-64 with a C/N ratio of 12.22–18.37. The use of laboratory silage fermentation of oilseed radish leaf mass, which is consistent with the findings of Mähnert et al. (2005) and Abu-Dahrieh et al. (2011), ensured an increase in the C/N ratio for all experimental variants with an interval of 12.63–34.37, while maintaining the same trend within the phenological phases as in the variant before the use of silage fermentation. That is, the very process of silage of oilseed radish, which is confirmed by the peculiarities of the chemistry of silage fermentation of cruciferous crops (Kamalak et al., 2005; Raboanatahiry et al., 2021; Chen et al., 2023) allowed to optimize the variants by the C/N ratio.

The previous generalizations were confirmed in the assessment of the cumulative biogas and biomethane productivity of inoculated oilseed radish silage obtained from variants of different sowing dates at different phenological phases of harvesting (Figure 5.19).

The total volume of biogas production in the interval of harvesting phases (Figure 5.19 a) of leaf-stem mass was 2137–3643 mL with a maximum when using for preliminary silage fermentation the leaf-stem mass harvested in the flowering phase at the first sowing date of oilseed radish. The minimum value of this indicator was noted in the variant of the first sowing date for harvesting in the green pod phase. The level of variation of this indicator had different values within the combinatorics of the experimental variants. The maximum values of variation were determined for the fourth (C_v 4.48–5.74%), and the minimum – for the first sowing dates (C_v 1.69–3.88%). It should be noted that the achieved level of total biogas production is consistent with studies on biogas fermentation of oilseed radish agrobiomass in other studies. Thus, according to Belle et al. (2015), this figure was in the range of 2700–3100 mL. In the studies of Molinuevo-Salces et al. (2013, 2014, 2014a) it was at the level of 2200–3200 mL (in terms of the planted weight and silage options), and according to Carvalho et al. (2011) it reached the level of 3500–3700 mL. In comparison to other representatives of the cruciferous family (according to Herrmann et al. (2016), Maier et al. (2017), Liebetrau et al. (2021), Słomka & Oliveira (2021) and Lallement et al. (2023)) silage-fermented biomass of oilseed radish can be attributed to a crop with high biogas potential in comparison with such typical representatives as white mustard, spring and winter rape, and some wild species of cruciferous plants.

The difference in the variation of the indicator value can be explained by differences in the chemical composition of the leaf-stem mass determined for different phenological phases and harvesting dates, which led to differences in the chemical composition of the silage in the corresponding variant of the experiment. These are the reasons noted in the studies by Kalyuzhnyi et al. (2009), Borreani et al. (2018) and Lallement et al. (2023) from the point of view of the main factors that determine the potential biogas productivity of pretreated agrobiomass through silage fermentation.

The index of cumulative biomethane productivity (different variants of the experiment (Figure 4b) was determined in the range of 1215–1963 mL with a similar distribution within the variants of phenological development and sowing dates with an increase in the total variation to the average long-term value to the level of C_v 4.08–8.40%. At the same time, for all terms of biomass harvesting, the fourth term had the highest level of variation with an index of 1.73 before the first sowing dates. This confirms the previously made conclusions about the peculiarities of the chemical composition of oilseed radish silages of summer sowing in terms of the presence of organic acids and the content of the main components, which, according to the study by Molinuevo-Salces et al. (2013), caused fluctuations in the share of methane in the total biogas composition and an increase in the share of other biogas components. These conclusions are confirmed by estimating the share of methane in the generated biogas volume (Figure 3c), where, in fact, for the fourth sowing term, an average minimum level of this indicator was noted at 54.34% (with C_v 8.27–10.96%). The highest proportion of methane was noted on average for the phenological phase s of selection for the third sowing term with an average of 55.45% in the overall combination of experimental variants (at Cv 4.27–6.76%). At the same time, it should be noted, based on the interannual variability of indicators, a certain constancy of the intensity of anaerobic fermentation of oilseed radish silage, which is consistent with the findings of Rabemanolontsoa & Saka (2013), Bumbiere et al. (2022) on the relative species stability of agrobiomass of potential candidates for biogas production and the findings of McDonald et al. (1991), Herrmann et al. (2011, 2012) and Auxenfans et al (2017) on a certain leveling of the basic structure of chemical composition indicators under certain pretreatment procedures for biogas fermentation, including preliminary silage. According to Herrmann et al. (2016), for cruciferous crops, including fodder radish, the cumulative biomethane production for autumn sowing (intermediate cultivation) ranges (in terms of volume) from 900–1400 mL with a methane share of 53.9–57.3%. A number of other studies provide data on close values of the noted intervals (Carvalho et al., 2011, Suominen et al., 2012; Molinuevo-Salces et al., 2013, 2014, 2014a; AL-Huqail et al., 2022).

Based on the comparison of the results of the cumulative level of biogas productivity and the cumulative level of biomethane production, the specific methane yields of oilseed radish silages from different variants were in the range 201.03–319.66 $L_N\,kg^{-1}{}_{ODM}\,d^{-1}$ (group C_v 12.95%) (the minimum was noted in the variant of the first sowing date for the green pod phase, and the maximum – in the variant of the first sowing date for the flowering phase). The average value of this indicator for the budding phase was 278.92 $L_N\,kg^{-1}{}_{ODM}\,d^{-1}$, for the flowering phase 292.45 $L_N\,kg^{-1}{}_{ODM}\,d^{-1}$, and for the green pod phase 237.54 $L_N\,kg^{-1}{}_{ODM}\,d^{-1}$.

Among the sowing dates, the maximum level of specific methane yields was achieved during the years of research at the fourth sowing date of 276.47 $L_N\,kg^{-1}{}_{ODM}\,d^{-1}$, and the minimum – at the third sowing date of 263.12 $L_N\,kg^{-1}{}_{ODM}\,d^{-1}$. This confirms the conclusions made earlier about the influence of changes in the biochemical composition of oilseed radish leaf biomass due to the shift in terms from early spring to summer on the features of the overall biogas productivity of the silage mass. In particular, this is an increased content of crude protein with a reduced content of crude fiber against the background of an increased content of nitrogen-free extractives, which forms optimal conditions for the intensity of biogas fermentation (Dandikas et al., 2014).

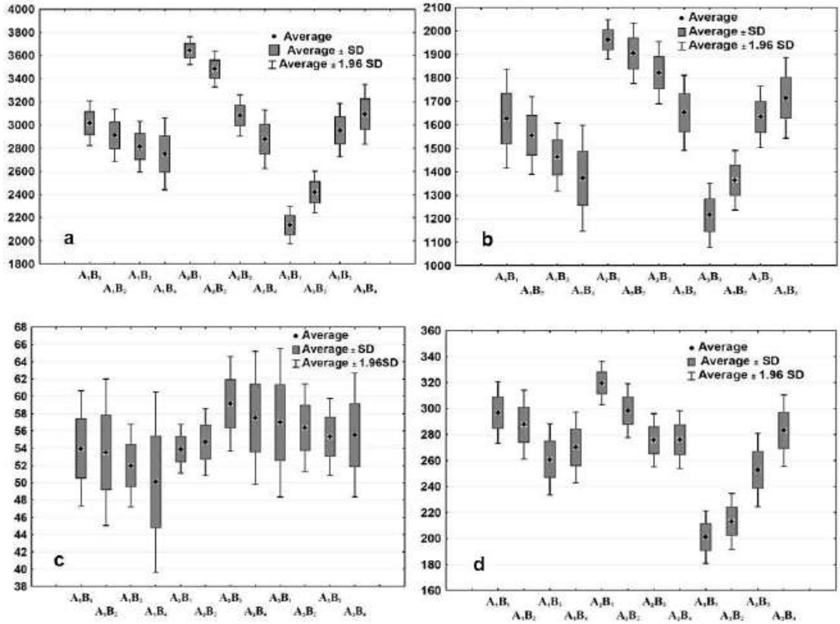


Figure 5.19 – Statistical evaluation of biogas productivity of oilseed radish silages (inoculum subtracted) obtained from plant mass of different sowing and harvesting periods, 2020–2022 (a – cumulative biogas production during the experimental period (mL); b – cumulative biomethane production during the experimental period (mL); c – methane content (%); d – specific methane yields of oilseed radish silages from different variants (LN $kg^{-1}{}_{ODM}$ d^{-1}); A_nB_n – indicates the combinatorics of options according to Table (Tsytsiura, 2023a)

The determined interval for specific methane yields falls within the interval established in a number of studies specifically for the radish genus 170–350 L_N $kg^{-1}{}_{ODM}$ d^{-1} (Carvalho et al., 2011; Herrmann et al., 2016; Molinuevo-Salces et al., 2013, 2014, 2014a) although there is an upper limit of up to 350–380 L_N $kg^{-1}{}_{ODM}$ d-1 and a lower limit of 120–150 L_N $kg^{-1}{}_{ODM}$ d^{-1} (Amon et al., 2007; Belle et al., 2015).

The cumulative curves of biomethane yield for different variants of research (Figure 5.20) confirm the conclusions made about the specifics of biomethane productivity from different variants of oilseed radish silage. At the same time, the maximum level of cumulative biomethane accumulation due to digestate inoculum was 656 mL over a period of 60 days of anaerobic fermentation, which corresponds to a sufficient level of cofermentation (Jankowska et al., 2017).

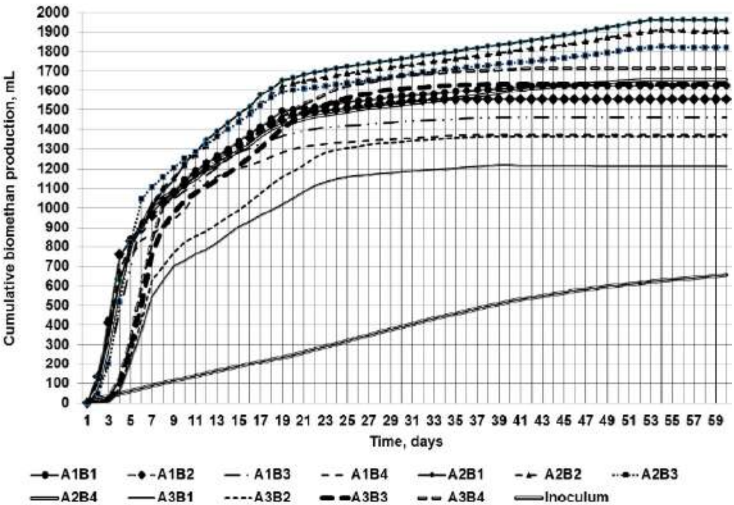


Figure 5.20 – Cumulative biomethane production during the experimental period of oilseed rape silages (inoculum subtracted) obtained from plant mass of different sowing and harvesting dates, mL (average adjusted for biomethane productivity of inoculum and standardized dry gas indicators for 2020–2022 for the total number of observations for each variant) (A_nB_n – indication of combinatorial variants according to Table 5.31) (Tsytsiura, 2023a)

The cumulative curves correspond to the nature of the Gompertz growth curves (Lay et al., 1997), correlate adequately with the specified interval of values in the context of experimental variants, and have a complex shape mainly in the period of 3–21 days of fermentation. Taking into account the statement of Wang (2010), this character indicates the oscillatory nature of the formation of the indicator at the points of fixation with different ordinal placement of indicators with a pronounced downward structure of values in the dynamics. This is confirmed by the data in Figure 4b for each of the experimental variants when averaging each daily observation point.

The dynamics, while generally similar in the ordinal height of the graphs, has certain differences. Within the variant for the budding phase (indexing of variants A_1), an intensive increase in methane emission was noted on day 3–5 and dominated by oscillatory maxima in the interval of 7–10 days. The period of minimal biomethane activity was observed from day 23, and the complete cessation of the process from day 35–43. The most complicated idiogram of the graph for the budding phenological phase was observed for the variant of the fourth sowing date. A rather short lag period was established (average 1.32 ± 0.15 days).

For the phenological phase of flowering (indexing of variants A_2), a more smoothed character of the graph was noted. An intensive increase in methane emission was observed on day 3–4, followed by oscillatory maxima in the interval of 7–13 days. The period of minimal biomethane activity was observed from 26–29 days, and the complete cessation of the process from 39–42 days. The most complicated idiogram of the graph for the flowering phenological phase was noted for the variant of the first and fourth sowing dates of oilseed radish. The duration of the lag period increased and averaged 1.49 ± 0.13 days.

For the phenological phase of the green pod (indexing of variants A3), a complex oscillatory nature of the graph (three peak values) was noted. There was an intensive increase in methane emission on day 5–7 followed by oscillatory maxima in the interval of 13–19 days depending on the sowing date (indexing of variants B_1–B_4). The period of minimal biomethane activity was observed from 22–25 days, and the complete cessation of the process from 55–58 days. The most complicated idiogram of the graph for the flowering phenological phase was observed for the variant of the first and fourth sowing dates of oilseed radish. The duration of the lag period was maximum for this phenological phase for all sowing dates and averaged 2.09 ± 0.65 days with a maximum for the first sowing date.

The mathematical expression of the curves for the research variants (Figure 5.21a) in terms of cumulative biomethane productivity corresponds to the classical Gompertz functional dependence for the cumulative nature of growth, described by classical equation 5.8–5.9. This is confirmed by the results of approximating the actual curve points to the model functions with the estimation of the correlation and prognostic components (RMSE and RRMSE) (Table 5.37). This mathematical relation is fully consistent with the mathematical models of biogas production from both raw plant material of bioenergy crops and subjected to various preliminary procedures of preparation for the final biofermentation process and is reflected in a number of publications (Parker et al, 2005; Carvalho et al., 2011; Triolo et al., 2011; Podkówka, 2012; Thomsen et al., 2014; Batstone et al., 2015; Herrmann et al., 2016; Einarsson et al., 2017; Pabón-Pereira et al., 2020; von Cossel et al., 2021; Tasnim et al., 2022; Fajobi et al., 2023).

At the same time, a number of features were noted that distinguish oilseed radish as a potential candidate for biogas production. In particular, the value of the coefficient k_1 (the first order decay constant (day^{-1})) in the equation of dependence on the anaerobic fermentation time (Table 6) determined for fodder radish in the studies of Herrmann et al. (2016) was in the range of 0.190–0.273, although among cruciferous crops in his studies, the value of this indicator was the lower limit of 0.144. In Słomka & Oliveira's (2021) research for white mustard, based on the analysis of the presented curves, this coefficient had a lower limit of 0.090–0.100. It is also reported (Ahlberg & Nilsson, 2015) that the nature of cumulative curves of biogas production can have a complex oscillatory character due to the specific biochemical composition of the biomass taken for fermentation, which can increase the value of this coefficient k at the starting sections of the curve and reduce its value for the overall analysis of the graph on the general abscissa of the graph. The same conclusions regarding the wide-interval value of the k_1 coefficient were noted in the studies of Herout et al. (2011) and Maier et al. (2017) At the same time, Fajobi et al. (2023) and Pabón-Pereira et al. (2020) noted that greater intensity of ordinal growth of the cumulative biogas production curve is characteristic of biomass with a lower dry matter content, rich in proteins and nitrogen-free extractives. This is confirmed by the results presented in the case of the budding phase, especially of the fourth sowing term, where a similar character of the biochemical composition of the plant mass is noted (Tables 5.36, 5.37) with a value of k_1 in the range of 0.122–0.134.

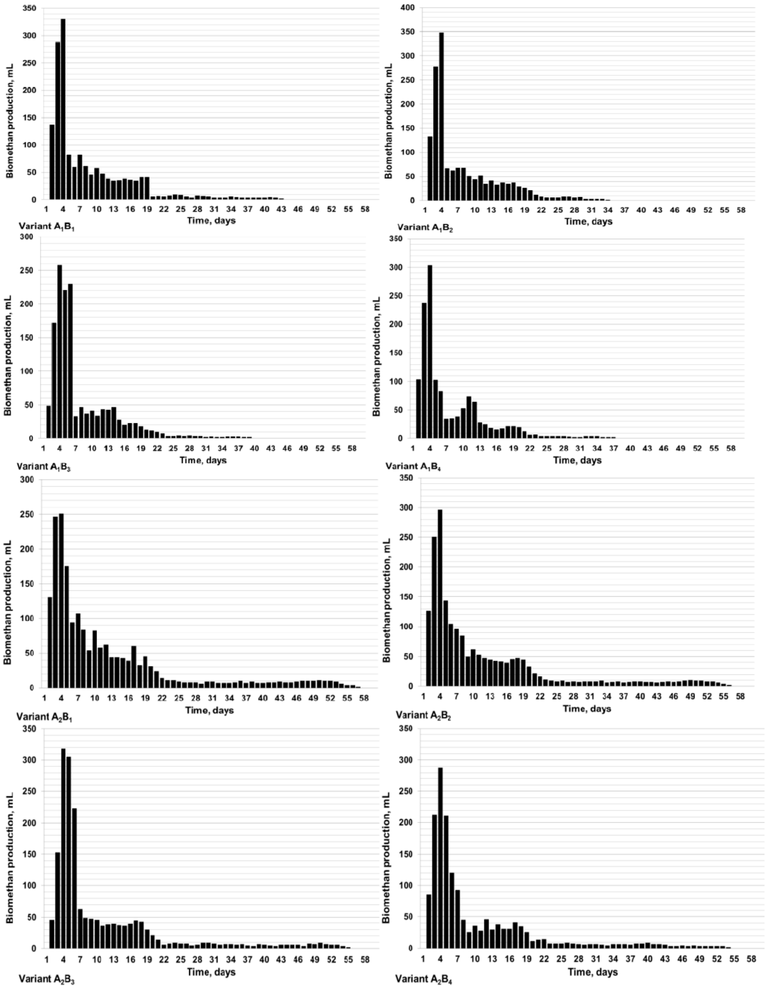
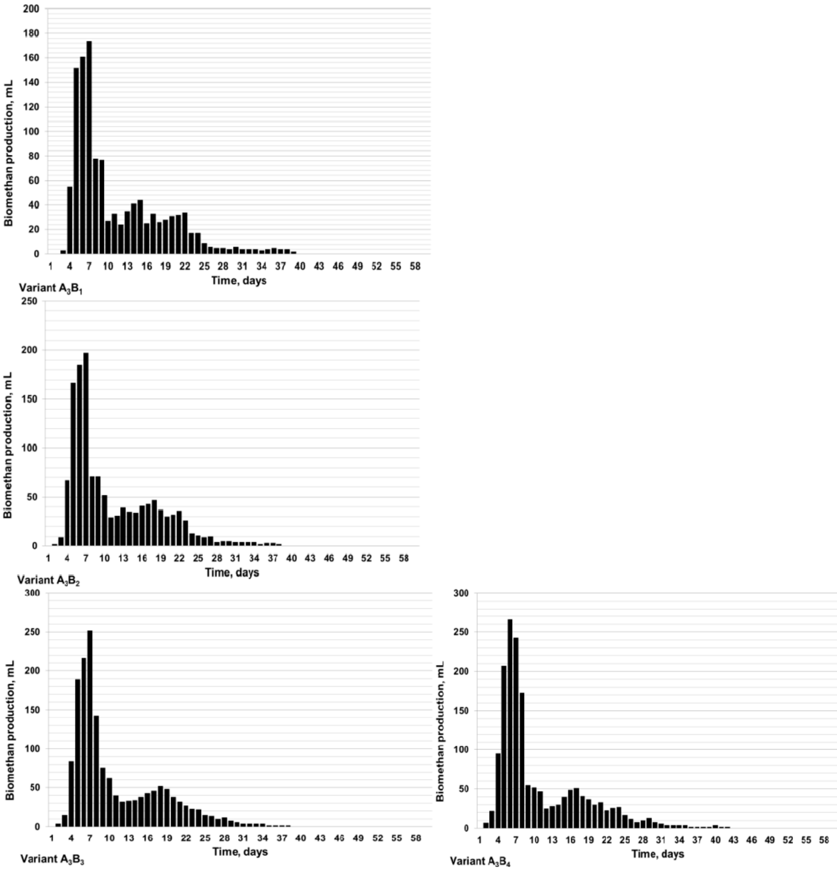


Figure 5.21 – Biomethane production during the experimental period of oilseed rape silages (inoculum subtracted) obtained from plant mass of different sowing and harvesting dates (average adjusted for biomethane productivity of inoculum and standardized dry gas values for 2020–2022 for the total number of observations for each variant) (Tsytsiura, 2023a)



Continued Figure 5.21 – Biomethane production during the experimental period of oilseed rape silages (inoculum subtracted) obtained from plant mass of different sowing and harvesting dates (average adjusted for biomethane productivity of inoculum and standardized dry gas indicators for 2020–2022 for the total number of observations for each variant) (Tsytsiura, 2023a)

Table 5.37

Functional expression of the cumulative biomethane and biomethane productivity of oilseed radish silages (inoculum subtracted) obtained from plant mass of different sowing and harvesting periods (based on average data for the period 2020–2022) (Tsytsiura, 2023a)

Variant*	Equation of dependence on the time of anaerobic fermentation (t)	Parameters of the equation		Statistical parameters for assessing the reliability of fitting the actual dynamics to the theoretical expression of the equation				
		y_m	k_1	S	$R^2_{(adj.)}$	RMSE	RRMSE	*p*
cumulative biomethan production (y) at time t (mL)								
A_1B_1	$y(t) = y_m\left(1-e^{(-k_1t)}\right)$	1625.533	0.122	45.700	0.985	128.91	18.96	*<0.001*
A_1B_2		1564.910	0.129	46.828	0.980	129.47	19.15	*<0.001*
A_1B_3		1473.787	0.129	62.617	0.961	132.28	19.58	*<0.001*
A_1B_4		1380.248	0.134	44.167	0.975	130.93	19.21	*<0.001*
A_2B_1		1917.568	0.097	54.127	0.982	129.11	19.07	*<0.001*
A_2B_2		1862.261	0.102	54.770	0.980	129.61	19.18	*<0.001*
A_2B_3		1784.985	0.111	78.609	0.961	132.37	19.64	*<0.001*
A_2B_4		1626.935	0.110	60.126	0.969	131.68	19.59	*<0.001*
A_3B_1		1265.749	0.080	73.296	0.950	134.94	19.97	*<0.001*
A_3B_2		1422.200	0.080	81.548	0.951	134.21	19.88	*<0.001*
A_3B_3		1635.270	0.068	96.530	0.950	135.11	20.05	*<0.001*
A_3B_4		1767.454	0.087	101.153	0.955	133.89	19.57	*<0.001*

biomethan production (y) at time t (mL)

Variant*	Equation of dependence on the time of anaerobic fermentation (t)	Parameters of the equation				Statistical parameters for assessing the reliability of the fitting				
		a	b	c	d	S	$R^2_{(adj.)}$	RMSE	RRMSE	p
A_1B_1	$y(t) = \dfrac{a+bt}{1+ct+dt^2}$	-5.721	5.070	-0.322	0.028	12.476	0.952	78.96	8.69	<0.001
A_1B_2		-4.237	6.525	-0.417	0.049	13.569	0.943	79.39	8.87	<0.001
A_1B_3		-2.131	7.891	-0.496	0.068	13.968	0.936	81.12	9.14	<0.001
A_1B_4		-1.148	9.446	-0.539	0.080	14.107	0.927	83.56	9.75	<0.001
A_2B_1		-40.878	41.926	-0.547	-0.108	9.951	0.961	76.97	8.35	<0.001
A_2B_2		-27.221	30.650	-0.543	0.097	11.468	0.954	78.27	8.47	<0.001
A_2B_3		-2.497	8.973	-0.433	0.052	12.319	0.960	77.18	8.59	<0.001
A_2B_4		-6.290	14.139	-0.491	0.071	8.099	0.974	73.27	7.52	<0.001
A_3B_1		-3.877	3.804	-0.275	0.019	14.563	0.905	90.49	11.18	<0.001
A_3B_2		-13.283	5.989	-0.336	0.031	12.186	0.917	87.29	10.57	<0.001
A_3B_3		-4.278	4.741	-0.309	0.024	13.741	0.914	88.14	10.91	<0.001
A_3B_4		-5.721	5.070	-0.322	0.028	12.477	0.950	78.81	8.69	<0.001

* – in accordance with the combinatorics of options according to Table 5.31

Conversely, for the green pod phase, with a decrease in crude protein content, an increase in crude fiber content, and a decrease in the content of nitrogen-free extractives, its value was in the range of 0.068–0.087. Due to this, the standard error of the graphs approximation naturally increases consistently when comparing the budding and flowering phenophases and confirms the conclusions drawn from the analysis of individual graphs of biomethane production for each experimental variant.

As for the mathematical analysis of the dynamics of biomethane production, taking into account the steady downward oscillatory dynamics, the presence of several peaks on the general downward curve, and the graphical dependence which was selected on the basis of the approximation process using the CurveExpert Professional software package is a linear and quadratic relationship that forms a complex curve configuration with a consistent peak increase at the 3–7th fixation point and a consistent steady decrease of hyperbolic character ($1(x(t)^{-1})$) (according to Gavril and Schönheim (1982)). This character of the curves, the level of approximation of which for all variants of the experiment was confirmed for the level of significance of 0.1% ($p<0.001$) indicates that the process of biomethane production from oilseed radish silage is an intensively decaying process, the main productive component of which is concentrated in the fixation cycle of 4–7 days, and the final process of productive biomethane production does not reach the full cycle of the selected experimental duration of anaerobic digestion (in our case, 60 days) (as indicated by the ratio of the coefficients a and b against the background of low values of the coefficients d according to Bardsley & Childs (1975)).

Additional indicators of the kinetics of biomethane production from oilseed radish silage (inoculum subtracted) (Table 5.38) allowed us to determine the features characteristic of oilseed radish in comparison with other traditional bioenergy crops from the cruciferous family. Thus, the previously analyzed indicator of methane concentration in the total biogas volume produced averaged 54.91% (with a range of 49.92–59.11%), which corresponds to the range of 53.9–57.3 for fodder radish determined by Herrmann et al. (2016) and determined by (Carvalho et al, 2011; Belle et al., 2015) at the level of 50–60 % for oilseed radish in single-component or multicomponent anaerobic digestion.

Taking into account that the controlled anaerobic process leads primarily to a gas mixture of 51–75% methane (Badger et al., 1979; Zubr, 1986; Mohanty et al., 2022) and for traditional cruciferous crops this figure ranges from 51.3-62.8% (Herrmann et al, 2016; Rahman et al., 2018; Kılıç et al., 2021; Ţîţei, 2021, 2022) oilseed radish biomass in the variant of preliminary sludge fermentation can be effectively utilized as a component of biogas production.

It has been established that from the point of view of the performance indicators of the kinetics of biogas production and the actual proportion of methane, it is optimal to harvest oilseed radish biomass with subsequent silage for biogas fermentation in the flowering phase (BBSN 64–67). For this phase, the average methane content in the total biogas production was 56.35%, with biochemical methane potential (BMP_{Gomp}) at 307.09 L_N kg^{-1}_{ODM} d^{-1}, specific methane yields (SMY) (Figure 5.31d) of 292.45 L_N kg^{-1}_{ODM} d^{-1} (share of SMY/BMP_{Gomp} 95.23%) and maximum specific methane production rate (R_m) at 31.67 L_N kg^{-1}_{ODM} d^{-1}. The values of these indicators for the budding phase (BBCH 64–67) were 52.31%, 278.92 L_N kg^{-1}_{ODM} d^{-1}, 285.51 L_N kg^{-1}_{ODM} d^{-1} (the share of SMY/BMP_{Gomp} 97.69%) and 25.72 L_N kg^{-1}_{ODM} d^{-1}, respectively. For the phenological phase of the green pod (BBCH 73–75) was at the level of 55.97%, 237.54 L_N kg^{-1}_{ODM} d^{-1}, 244.30 L_N kg^{-1}_{ODM} d^{-1} (share of SMY/ BMP_{Gomp} 97.24%) and 25.80 L_N kg^{-1}_{ODM} d^{-1}, respectively.

The efficiency of biogas productivity varied within the sowing dates. Averaged over the phenological phases budding-green pod (BBCH 50–75) for the first sowing period, the parameters of biogas production performance were as follows: methane content 54.90% with biochemical methane potential (BMP_{Gomp}) at the level of 284.36 L_N kg^{-1}_{ODM} d^{-1}, specific methane yields (SMY) (Figure 3d) 272.53 L_N kg^{-1}_{ODM} d^{-1} (the share of SMY/ BMP_{Gomp} 95.83%) and the maximum specific methane production rate (R_m) at the level of 27.64 L_N kg^{-1}_{ODM} d^{-1}. The ratio index for SMY and Rm in comparison to the first sowing term for the second to fourth sowing term, depending on the phenological phase of biomass selection, was at the level of 0.81–1.41 and 0.84–1.38, respectively. At the same time, taking into account the level of SMY (> 200 L_N kg^{-1}_{ODM} d^{-1}) according to the assessment of the potential of bioenergy crops (Amon et al., 2007; Vindis et al., 2009; Herrmann et al., 2016; Kılıç et al. 2021), all sowing dates of oilseed radish have a fairly high level of productive potential for biogas processing. According to the assessment of the maximum achievable potential for the phenological phase of budding and flowering, the first and second sowing dates had the optimum, and the third and fourth – for the green pod phase. This distribution pattern is primarily confirmed by the peculiarities of the biochemical composition of both raw biomass and biomass after silage fermentation. In particular, during the green pod phase, an intensive increase in the proportion of crude fiber was observed with a corresponding decrease in nitrogen-free extractives (NfE) (Tables 5.35–5.37).

Table 5.38

Biomethane production characteristics of oilseed rape silages (inoculum subtracted) depending on the sowing date and phenological phase of plants (average for 2020–2022 for the total number of observations for each variant) (Tsytsiura, 2023a)

Sowing date	Methane content (%)		BMP_{Gomp} (L_N kg^{-1}_{ODM})		R_m (L_N kg^{-1}_{ODM} d^{-1})		t_{50} (d)*		Lag period (λ) (d)***	
	$\bar{x}$	SD**	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
budding stage (BBCH 50–53)										
I	53.95	3.54	304.94	11.55	27.88	1.17	3.57	0.32	1.08	0.17
II	53.42[d]	4.53	298.97[c]	13.87	26.63[b]	1.29	2.96[b]	0.40	1.25[c]	0.13
III	51.96[b]	2.53	274.74[b]	14.17	24.98[b]	1.58	3.89[c]	0.25	1.51[b]	0.11
IV	49.92[b]	5.49	263.39[b]	14.35	23.40[a]	1.67	3.00[c]	0.25	1.47[b]	0.19
flowering stage (BBCH 64–67)										
I	53.90	1.32	344.13	7.06	33.74	1.25	4.50	0.50	1.18	0.12
II	54.69[c]	1.98	314.19[b]	8.38	32.69[b]	1.39	4.35[b]	0.42	1.46[c]	0.15
III	59.11[a]	2.50	280.30[a]	9.68	31.58[a]	1.47	3.61[a]	0.38	1.75[a]	0.10
IV	57.69[a]	4.11	289.75[a]	11.90	28.67[a]	1.61	3.91[a]	0.44	1.58[b]	0.14
green pod stage (BBCH 73–75)										
I	56.86	4.60	204.01	9.85	21.30	1.12	4.85	0.48	2.88	0.21
II	56.33[c]	2.72	222.29[b]	10.84	23.89[b]	1.21	5.38[b]	0.52	1.92[b]	0.17
III	55.27[b]	2.34	263.62[a]	13.84	28.55[a]	1.55	4.37[c]	0.63	1.83[b]	0.15
IV	55.42[b]	3.72	287.26[a]	14.98	29.46[a]	1.49	4.45[c]	0.58	1.71[b]	0.12

BMP_{Gomp}: biochemical methane potential derived from the modified Gompertz equation; Rm: maximum specific methane production rate; *t_{50}: half-life (counting from the beginning of methane emission); **SD: standard deviation; ***: in terms of days from hourly accounting in the ratio of 1 day = 24 hours; Significance levels in comparison with the first (I) sowing term: a – 0.1%; b – 1%; c – 5%; d – no significant difference.

Another possible factor in the advantage of later sowing dates for harvesting at the green pod stage is the appearance of pods with seed germs in the structure of the leaf-stem mass. It is during the fruiting period that intensive synthesis of fatty acids begins in oilseed radish (Tsytsiura, 2022) and an intensive increase in the concentration of glycosaminolates from 50 to 160 μmol g^{-1} is noted (Carlson et al., 1985; Prieto et al., 2019). Given the possible influence (inhibition) of glucosinolates on the intensity of biofermentation of the crude mass of cruciferous plant species (Barba et al. (2016); Sun et al. (2020); Bichsaem et al. (2021)). This issue may also be an additional factor in the reduction of SMY for oilseed radish at the fruiting stages (BBCH>70) and requires further study as it is an important factor in the effective use of traditional and less common cruciferous plant species for biofermentation for bioenergy needs.

Certain peculiarities were also noted for the indicator of anaerobic fermentation half-life (t_{50}). A number of studies have found that its value varies for different bioenergy crops in the range of 1.5–9.5 (Petersson et al., 2007; Vindis et al., 2009), and for cruciferous plants it ranges from 2.62–5.11, and in particular for fodder radish 2.68–3.69 (Carvalho et al., 2011; Herrmann et al., 2016). For oilseed radish, within the experimental variants, this indicator differed significantly (2.96–5.38) both in terms of biomass harvesting and sowing dates with a pronounced tendency of its growth (on average, in comparison with the budding phase (BBCH 50–53), the growth index was 1.22, and by the green pod phase (BBCH 73–75) it was 1.42) during the maturation of oilseed radish plants. Within the sowing dates, the trend is the opposite (the index of decrease in comparison with the first sowing date for the second term was 0.98, for the third term 0.92, for the fourth term 0.88). Based on this, a conclusion was made that confirms the analysis of the analysis of biomethane production graphs in terms of variants (Figure 5.21b) regarding the peak period in the anaerobic fermentation of oilseed radish silage on the 3rd–7th day of fixation, as well as the belonging of the kinetics of biomethane production from oilseed radish biomass to a high-amplitude pronounced damping process, which is consistent with the findings of Petersson et al. (2007) and Yen et al. This specificity of the process kinetics is also confirmed by the lag period (λ) in the range of 1.08–2.88 for different oilseed radish variants.

Such a short lag period was obtained in the study of Carvalho et al. (2011), where the process of biogas formation was observed on the second day after the laying of silage from oilseed radish biomass for anaerobic fermentation. This nature of the formation of the lag phase duration is explained by the results of Kim & Kim (2020), who found that the lag phase could be caused by the acidification by volatile fatty acid (VFA) accumulation and the initial VFA to volatile solid ratio. To reduce the lag-phase, the VFA/Alk ratio should be maintained below 0.4.

The initial VFA/VS ratio below 10% enhanced anaerobic digestion performance and digestion time reduction at a high protein loading rate. Taking into account the previous conclusions about the increase in both crude fat content and total fatty acid content due to the strengthening of fruit and seed formation subphases with a rich amino acid composition (Bell et al., 2000; Barthet & Daun, 2002; Ávila & Sodré, 2012) against the background of an increase in dry matter content during the green pod phase (BBCH 73–75), a longer lag period of 2.09 days (for comparison, the same indicator averaged by sowing dates for the flowering phase (BBCH 64–67) was 1.49 and for the budding phase (BBCH 73–75) – 1.33). The variable dynamics of the lag phase duration (λ) within the sowing dates is explained by the same reasons (according to Kim and Kim (2020)) for the ratio of biochemical components of silage-fermented oilseed radish leaf-stem mass noted in the assessment of the effect of sowing dates on the chemical composition of the silage substrate.

Based on the preliminary analysis, it should be noted that the biochemical composition of the substrate undergoing anaerobic fermentation will affect both the chemistry and the kinetics of the biogas formation process under appropriate temperature conditions. Such conclusions are consistent with the basic publications on this issue (Weißbach et al., 1995; Ofori and Becker, 2008; Carvalho et al. (2011); Rath et al, 2013; Dandikas et al. 2014; Herrmann et al. 2016; Lamba et al., 2016; Jankowska et al. 2017; Martínez-Gutiérrez 2018; Kılıç et al. 2021; Czubaszek et al. 2022; Lallement et al. 2023). The results of research in this area in the application to the anaerobic fermentation of oilseed radish silage are to some extent similar to the results of these scientists (Table 5.39). However, it should be noted that there are certain features that distinguish this system of indicators from the point of view of assessing the impact on the kinetics of the biomethane production process. Taking into account the values of the determined correlation coefficients, the SMY (specific methane yield) for oilseed radish silages (inoculum subtracted) was tendentially higher (the level of 'Moderate correlation' was taken into account (according to the recommendations of Dandikas et al, 2014)) with lower crude fiber content (CFb, coefficient of determination (dyx) 53.29%), higher organic dry matter (ODM, d_{yx} 19.36%), organic acid derivatives (SBVa, d_{yx} 20.25%; SAPa, d_{yx} 30.25%), alcohols (Alc, d_{yx} 23.04%), lactic acid (LA, d_{yx} 18.49%), but despite the higher concentration of these acids at a lower acidity of the substrate (at a higher numerical pH value) (pH A, d_{yx} 10.89%).

The R_m (maximum methane production rate) was significantly higher with lower crude fiber content (CFb, coefficient of determination (d_{yx}) 40.96%), higher crude ash content (CA, d_{yx} 18.49%), higher k_1 (first order decay constant, d_{yx} 54.76%) and lower silage substrate acidity (pH A, d_{yx} 7.80%). The t_{50} (half-life period) was tendentially higher due to higher crude fiber content (CFb, d_{yx} 53.29%), higher dry and organic dry matter content (DM, d_{yx} 43.56%; ODM, d_{yx} 29.16%), higher C/N ratio (d_{yx} 57.76%), lower content of a number of organic acid derivatives and silage fermentation alcohols (SBVa, La, SAPa, Alc: d_{yx} 28.09–67.24%), lower crude protein content (CP, d_{yx} 49.00%), lower crude ash content (CA, d_{yx} 60.84%), higher pH (lower acidity of the silage substrate) (d_{yx} 62.41%) with a lower value of k_1 (first order decay constant, d_{yx} 77.44%). The duration of the lag phase (λ) had the same dependence as the t_{50} (half-life period) due to the identity of its formation mechanism in the anaerobic fermentation system (Kim & Kim (2020)).

According to the level of the direct (G) and adjusted (G´) correlation graph, it was determined that the productive indicators of biogas yield SMY and R_m in the case of anaerobic fermentation of oilseed radish silage in the system of dependencies belong to the average deterministic ones in the applied complex of the correlation galaxy for 19 traits (according to Sokal & Rohlf, 2012; Lockwood, 2016)) with the level of determination according to the adjusted correlation graph (G´) at the level of 19.62% and 23.62%.

Table 5.39

Pearson's correlation coefficients of chemical components and methane production characteristics of all crop silage samples (for a joint system of matching variants–repetitions–years (N=144)) (Tsytsiura, 2023a)

1. DM*	2. ODM	3. CP	4. CF	5. CFb	6. CA	7. NfE	8. C/N	9. SBVa	10. Alc	11. pH	12. La	13. SAPa	14. y_m	15. k_1	16. MC	17. SMY	18. R_m	19. t_{50}	20. λ
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	200
1	0.59	-0.69	0.36	0.66	-0.60	0.12	0.54	-0.79	-0.77	0.78	-0.79	-0.70	0.08	-0.52	0.50	-0.43	0.04	0.66	0.60
2		-0.68	0.33	0.69	-0.61	0.63	0.73	-0.77	-0.74	0.75	-0.78	-0.68	0.26	-0.61	0.69	0.44	0.22	0.54	0.52
3			-0.26	-0.71	0.93	-0.66	-0.99	0.62	0.56	-0.59	0.64	0.41	0.44	0.80	-0.34	0.24	0.17	-0.70	-0.41
4				0.24	-0.30	0.08	0.31	-0.36	-0.26	0.39	-0.38	-0.28	-0.18	-0.26	0.28	-0.37	-0.16	0.48	0.34
5					-0.80	0.12	0.77	-0.80	-0.79	0.78	-0.83	-0.73	-0.38	-0.84	0.59	-0.73	-0.64	0.73	0.77
6						-0.61	-0.92	0.74	0.67	-0.72	0.76	0.52	-0.01	0.86	-0.40	0.22	0.43	-0.78	-0.48
7							0.59	-0.06	0.04	0.08	-0.08	0.27	0.02	-0.32	-0.03	0.36	0.01	0.29	-0.29
8								-0.66	-0.60	0.64	-0.69	-0.48	-0.32	-0.84	0.41	-0.24	-0.32	0.76	0.45
9									0.79	-0.78	0.75	0.72	-0.06	0.86	-0.66	0.45	-0.02	-0.82	-0.80
10										-0.76	0.77	0.73	-0.06	0.84	-0.63	0.48	-0.01	-0.76	-0.81
11											-0.69	-0.61	0.16	-0.67	0.75	0.33	0.28	0.79	0.77
12												0.52	-0.18	0.69	-0.63	0.43	-0.05	-0.53	-0.50
13													-0.07	0.76	-0.64	0.55	-0.02	-0.66	-0.56
14														-0.18	0.60	0.75	0.82	0.08	-0.34
15															-0.58	0.25	0.74	-0.88	-0.62
16																-0.22	0.20	0.45	0.66

(End of Table 5.39)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	200
17																	0.78	-0.37	-0.82
18																		-0.52	-0.56
19																			0.57
**10.2	11.2	10.8	5.6	12.6	11.4	4.7	11.3	11.5	11.1	11.1	10.7	9.9	5.0	12.1	9.3	8.4	5.8	11.4	11.0
***0.64	0.59	0.57	0.31	0.70	0.63	0.58	0.59	0.72	0.69	0.65	0.63	0.58	0.42	0.64	0.51	0.44	0.49	0.63	0.57

r = |0|–|0.4| No or weak correlation; r = |0.4|–|0.7| Moderate correlation; r = |0.7|–|1.0| Strong correlation. *DM: dry matter; ODM: organic dry matter; CF: crude fat; CP: crude protein; CFb: crude fibre; CA: crude ash; NfE: nitrogen-free extracts; C/N: carbon to nitrogen ratio; SBVa: sum of i-butyric, butyric, i-valeric, valeric and caproic acid; Alc: Sum of ethanol, propanol, 1,2-butanediol, 2,3-propanediol; pH: silage acidity; LA: lactic acid; SAPa: sum of acetic and propionic acid; y_m: is the maximum specific methane yield at theoretically infinite digestion time; k_1: first order decay constant; MC: methane content; SMY: specific methane yield; R_m: maximum methane production rate; t_{50}: half-life period; λ: lag phase period. ** Graf G; *** Graf G´. For a significance level of $p < 0.05$, the interval r = 0.16–0.20, for $p < 0.01$ r = 0.21–0.26, for $p < 0.001$ r > 0.26.

At the same time, the highest levels of determination were established for such indicators as k_1 t50 and λ with the corresponding value of the general correlation graph (G) at the level of 11.0–12.1 with the level of determination by the adjusted correlation graph (G´) at the level of dyx 32.72–40.70%. In the system of factor indicators, the highest level of determination by the size of the correlation graphs was established for the crude fiber content (CFb) (G at the level of 12.6, and G´ in the expression dyx 49.00%).

It should be noted that the acidity (pH) of the oilseed radish silage samples has a tendency to influence the biomethane productivity of substrates. Based on the fact that silages from cruciferous crops have a predominantly pH in the range of 3.5–5.3 and for radish 3.8–5.3 (Herrmann et al, 2016), optimization of silage acidity to the level of 4.6–5.0 positively affects the levels of biomethane production in terms of SMY and R_m and, given the established dependencies, allows for their conjugate growth with a decade-long decrease in acidity (respectively, an increase in the nominal pH) by at least 9.0–11.0%. These conclusions are consistent with the findings of Jayaraj et al. (2014), Cerón-Vivas et al. (2019), and Zhang et al. (2022).

The presence of a complex variation in the size of correlation graphs allowed us to conclude that the dependencies between the factors taken for the analysis of the kinetics and productivity of biomethane production from silage-fermented oilseed radish mass are more complex. Based on this, a system of graphical regression correlation of a number of indicators to the resulting SMY (specific methane yield, $L_N\ kg^{-1}{}_{ODM}\ d^{-1}$) was applied using the method of weighted least squares distances (Figure 5). The presented regression surfaces demonstrated the complex nature of the formation of the main resulting indicator SMY (specific methane yield) from the binary combination of a number of biochemical parameters of oilseed radish silage in the systematic comparison of the general combinatorics of options. Thus, in the system of dependencies SMY–C/N–NfE (Figure 5.22a), the maximum level of SMY (330–350 $L_N\ kg^{-1}{}_{ODM}\ d^{-1}$) is predicted to be formed at the content of nitrogen-free extractives (NfE) in the silage mass of oilseed radish at the level of 50–52$\%_{DM}$ at a C/N ratio of 20–22.

For the system of SMY–NfE–CP dependencies (Figure 5.22b), the same level of SMY can be predictably achieved at the following NfE values of 50–52$\%_{DM}$ at a crude protein content (CP) of 15–16$\%_{DM}$.

For the system of SMY–CF–NfE dependencies (Figure 5.22c), the level of SMY 312–340 $L_N\ kg^{-1}{}_{ODM}\ d^{-1}$ can be predictably achieved at the following values of the comparison factors NfE 48–50$\%_{DM}$, crude fat (CF) 3.1–3.2$\%_{DM}$.

For the SMY–CFb–NfE dependence system (Figure 5.22d), the level of SMY > 300 $L_N\ kg^{-1}{}_{ODM}\ d^{-1}$can be predictably achieved with the following values of the matching factors NfE 50–52$\%_{DM}$ and crude fiber (CFb) 20–23$\%_{DM}$.

For the system of SMY–CA–NfE dependencies (Figure 5.22e), the level of SMY >300 $L_N\ kg^{-1}{}_{ODM}\ d^{-1}$ can be predictably achieved at the following values of the matching factors CA 14–16$\%_{DM}$ and NfE 48–50$\%_{DM}$.

For the SMY–CF–CP system (Figure 5.22f), the level of the maximum resulting SMY index >300 $L_N\ kg^{-1}{}_{ODM}\ d^{-1}$ is achievable at CF values of 3.2–3.35$\%_{DM}$ and CP values of 14–16$\%_{DM}$.

For the SMY–CFb–CP system (Figure 5.22g), the maximum resulting SMY > 360 $L_N\ kg^{-1}{}_{ODM}\ d^{-1}$ is achieved at CFb 18–22$\%_{DM}$ and CP 8–12$\%_{DM}$.

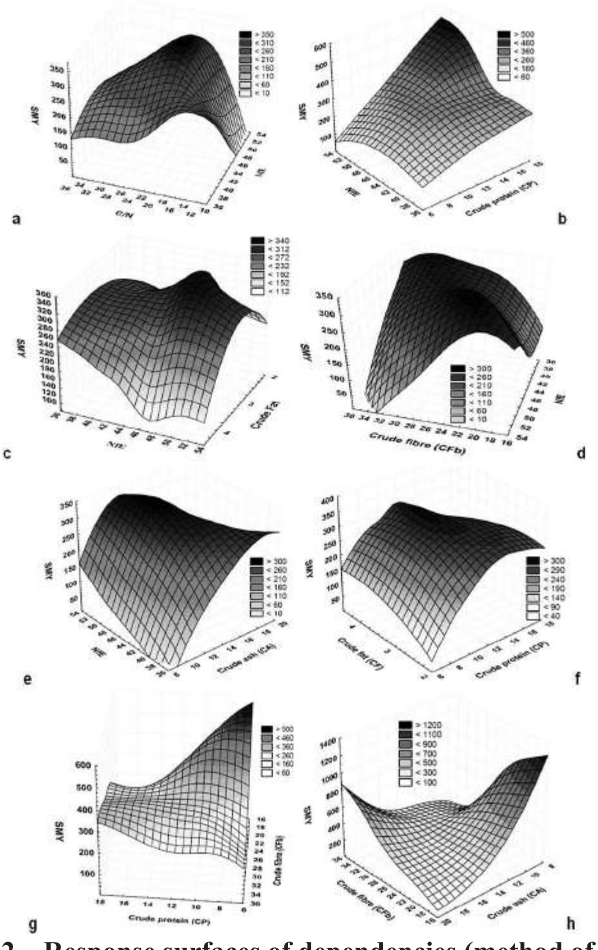


Figure 5.22 – Response surfaces of dependencies (method of weighted least squares distances) of the ‘specific methane yield’ (SMY) indicator depending on the basic chemical composition of oilseed radish silages (inoculum subtracted) (in the summary system of variants–repeat–years). Regression comparisons: a: SMY–C/N–NfE; b: SMY– NfE–CP; c: SMY–CF–NfE; d: SMY–CFb–NfE; e: SMY–CA–NfE; f: SMY–CF–CP; g: SMY–CFb–CP; h: SMY–CFb–CA (Tsytsiura, 2023a)

For the SMY–CFb–CA system (Figure 5.22h), the level of maximum resulting SMY up to 500 L_N kg^{-1}_{ODM} d^{-1} is achieved at CFb 16–18%$_{DM}$ and crude ash (CA) 10–12%$_{DM}$ or (binary peak reaction surface) in the variant: CFb 26–28%$_{DM}$ and CA 18–20%$_{DM}$.

The constructed reaction surfaces are fully consistent with the results of the evaluation of a significant number of bioenergy crops for biogas productivity (Herrmann et al., 2016; Oleszek et al., 2020; Aravani et al., 2021; Lallement et al., 2023) and take into account the special characteristics of oilseed radish under different technological solutions, taking into account the timing of sowing and the timing of leaf mass selection for anaerobic fermentation.

Oilseed radish as a multidisciplinary bioenergy crop has demonstrated high biogas and biomethane potential with the possibility of long-term use and biomass harvesting in a wide range of phenological phases. From the point of view of the potential share of methane yield in combination with biogas productivity for the phenological phase of budding (BBCH 50–53) and flowering (BBCH 64–67) with the subsequent process of silage fermentation, the variant of the first sowing term with the level of biochemical methane potential (BMP_{Gomp}), respectively, 304.94 and 344.13 L_N kg^{-1}_{ODM} d^{-1}, specific methane yield (SMY) 296.91 and 319.66 L_N kg^{-1}_{ODM} d^{-1} with a maximum specific methane production rate (R_m) 27.88 and 33.74 L_N kg^{-1}_{ODM} d^{-1}. For the phenological phase of the green pod (BBCH 73–75), the variant of the fourth sowing term (summer term as a possible option for intermediate cultivation of oilseed radish in crop rotation) with the corresponding parameters was determined as expedient: BMP_{Gomp} 287.26 L_N kg^{-1}_{ODM} d^{-1}, SMY 283.18 L_N kg^{-1}_{ODM} d^{-1} at R_m 29.46 L_N kg^{-1}_{ODM} d^{-1}.

The optimal biochemical idiotype of oilseed radish plants was determined in the system of pairwise correlation and multiple regression comparison from the point of view of realization of biomethane potential of the crop when harvesting its biomass in the interphase period of budding–green pod (BBCH 50–75): CP 14–18%$_{DM}$, CFb 16–20%$_{DM}$, CA 14–18%$_{DM}$, CF 3.1–3.2%$_{DM}$, NfE 48–50%$_{DM}$ at a C/N ratio of 20–22 with the acidity of the subsequent silage-fermented mass at the level of pH 4.6–5.0.

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CONCLUSION

Summarizing the multifaceted portfolio of olive radish in the system of its multipurpose use for the rehabilitation of degraded soils and lands on the principles of climate neutrality, the main results should be noted:

1. According to the results of a multi-year study cycle, oil radish showed high productivity and adaptability. This is confirmed by the average indicators of its long-term productive and biochemical portfolio, which for the spring sowing period had the following parameters: formed aboveground biomass (BM) 24.04 t ha-1, formed root biomass (RBM) 8.7 t ha^{-1}, soil coverage at 70 days after sowing (GC70) 73.77%, crude protein content (CP) 15.56% $_{DM}$, crude fat (CF) 3.98% $_{DM}$, cellulose 21.73% $_{DM}$, hemicellulose 10.95% $_{DM}$, phosphorus 0.62% DM, potassium 3.63%$_{DM}$, calcium 0. 96%$_{DM}$, sulfur 0.42%$_{DM}$, glucosinolates (GSL) 13.57 µmol $g^{-1}{}_{DM}$, C/N ratio 16.02, Residue quality (RQ) 84.99%$_{DM}$, Carbohydrates (CH) 67.08%$_{DM}$, GSL productivity 41.2 mol ha^{-1}. For the summer sowing period, similar parameters were as follows: BM 18.34 t ha^{-1}, RBM 5.50 t ha^{-1}, GC70 50.74%, CP 19.16%$_{DM}$, SF 4.61%$_{DM}$, cellulose 24.43 %$_{DM}$, hemicellulose 12.85%$_{DM}$, phosphorus 0.63%$_{DM}$, potassium 3.96%$_{DM}$, calcium 1.01%$_{DM}$, sulfur 0.48%$_{DM}$, GSL 19.70 µmol $g^{-1}{}_{DM}$, C/N ratio 13.30, Residue quality (RQ) 81.03%$_{DM}$, CH 61.93%$_{DM}$, GSL productivity 54.90 mol ha^{-1}. Using the above data block with the application of Multi-criteria decision aiding (MCDA), the possibility of multi-purpose use of oil radish in the criterion system of multi-service cover crop (MSCC) was proved in the following order of decreasing technological significance for the conditions of unstable hydrothermal regime of its vegetation period on soils with an average level of soil fertility potential (averaged for both sowing dates): 'Green manure' – 'Fodder' – 'Cover crop' – 'Biogas' – 'Catch crop'.

2. Oilseed radish was sensitive to water extracts of 23 perennial weed species tested in the range of concentrations of 0.25–16.0% (w/v). The range growth of weed species allelopathic potential on their impact on seed germination according to APG averaged for two variants of germination was as follows: *Cuscuta campestris* Yuncker (APG (average for germination variants) 0.68) > *Acroptilon repens* (L.) de Candolle (0.66) > *Plantago major* L. (0.63) > *Linaria vulgaris* Mill. (0.61) > *Equisetum arvense* L. (0.60) > *Cirsium arvense* (L.)

Scopoli, *Convolvulus arvensis* L. (0.59) > *Agropyron repens* (L.) Gould (0.58) > *Onopordum acanthium* L. (0.57) > *Cyclachaena xanthiifolia* Nuttall (0.55) > *Sonchus arvensis* L., *Cichorium intybus* L., *Plantago lanceolata* L. (0.54) > *Artemisia absinthium* L. (0.51) > *Echium vulgare* L., *Rumex acetosella* L. (0.48) > *Artemisia vulgaris* L. (0.47) > *Arctium lappa* L. (0.46) > *Cynodon dactylon* (L.) Pers., *Rumex confertus* Willdenow (0.44) > *Carduus acanthoides* L., *Taraxacum officinale* Weber (0.39) > *Achillea millefolium* L. (0.36). It has been established that "speed of germination" and "coefficient of velocity of germination" can be used as effective indicators for assessing the allelopathic sensitivity of test objects. Thus, they were respectively 5–7 germinated seeds per day for the percentage of germinated seeds for 7–9 days over 30% of the total number laid for germination, and for species with weak allelopathic activity, respectively, 10–11 germinated seeds per day of germination and the percentage of germinated seeds per 7–9 days more than 4–15% of the total in the case of oilseed radish in allelopathically adhesive species at an extract concentration of 4.0%. Taking into account the classification of allelopathic potential (Smith, 2013) with 47.8% of the researched species belonging to the Non-allelopathic (NA) class and the absence of weeds belonging to the class Highly allelopathic (HA) for the test object, radish oilseed should be considered as an effective candidate for its application in the system of weeds biological control of sidereal and mediator application in traditional rotational schemes of cultivation of major crops of the non-cruciferous group.

3. Oilseed radish was very sensitive to the water extracts of the 54 weed species tested in the range of concentrations 0.25–16% (w v^{-1}). Soil alleviated the allelopathic impact of the weed extracts. APG indexes allowed to cluster weed extracts in 10 intervals of 0.05 included in the range 0.26–0.72. Twenty seven species (50.0% of the total tested) had APG values higher than 0.50. The APG values calculated from data recorded from Petri dish and soil bioassays allow to classify the weed species from more to less harmful on oilseed radish, in the following order: *Raphanus sativus* L. var. *oleiformis* Pers. (0.68–0.72) > *Amaranthus retroflexus* L. (0.64–0.67) > *Chenopodium album* L. (0.63–0.67) > *Raphanus raphanistrum* L. (0.63–0.67) > *Papaver rhoeas* L. (0.61–0.68) > *Brassica campestris* (L.) Janchen (0.60–0.67) > *Brassica napus* L. (0.60–0.67) > *Sinapis arvensis* L. (0.62–0.64) >

Sinapis alba L. (0.59–0.62) > *Fumaria officinalis* L. (0.60–0.62) > *Galinsoga parviflora* Cavanilles (0.57–0.62) > *Tripleurospermum maritimum* (L.) Koch (0.57–0.61) > *Portulaca oleracea* L. (0.57–0.60) > *Rocket-cress* Brown (0.56–0.59) > *Lepidium draba* L. (AP = 0.54–0.57) > *Brassica napus* L. (0.53–0.57) > *Sisymbrium loeselii* L. (0.54–0.57) > *Chondrilla juncea* L. (0.52–0.55) > *Galium aparine* L. (0.49–0.58) > *Echinochloa crus-galli* (L.) P.Beauv. (0.47–0.57) > *Senecio vernalis* (Waldstein & Kitaibel) Alexander (0.50–0.52) > *Solanum nigrum* L. (0.54–0.55) > *Descurainia sophia* (L.) Prantl (0.49–0.53) > *Thlaspi arvense* L. (0.46–0.52). The weeds were classified according to their APSG and APRG indexes, and the percentage of appearance frequency (F) in oilseed radish fields, from more to less harmful, as: *Amaranthus retroflexus* (0.48, 0.64, 62.33–71.67) > *Echinochloa crus-galli* (L.) P.Beauv (0.41, 0.65, 58.67–71.67%) > *Setaria glauca* L. (0.53, 0.61, 56.00–62.33%) > *Chenopodium album* L. (0.55, 0.47, 42.67–54.00%) > *Brassica napus* L. (0.60, 0.67, 5.00–53.50%) > *Galinsoga parviflora* Cavanilles (0.63, 0.37, 25.00–46.33%) > *Sinapis alba* L. (0.60, 0.64, 4.30–42.80%) > *Tripleurospermum maritimum* (L.) Koch (0.41, 0.49, 16.33–42.67%) > *Raphanus sativus* L. var. *oleiformis* Pers. (0.65, 0.58, 3.50–40.70%) > *Polygonum lapathif*olium (L.) Delarbre (0.48, 0.36, 24.67–34.33%) > *Setaria viridis* (L.) Palisot de Beauvois (0.41, 0.35, 16.67–25.00%) > *Rocket-cress* Brown (0.56, 0.50, 6.67–22.67%) > *Brassica campestris* (L.) Janchen (0.47, 0.61, 19.33–22.33%) > *Lactuca serriola* L. (0.56, 0.57, 10.67–21.67%) > *Thlaspi arvense* L. (0.38, 0.64, 7.67–21.0%) > *Senecio vernalis* (Waldstein & Kitaibel) Alexander (0.65, 0.58, 11.00– 17.67%) > *Lepidium draba* L. (0.57, 0.71, 7.11–8.92%). Considering the obtained allelopathic potential for different types of weeds, the maximum harmfulness of weed cenosis in the oilseed radish agrophytocoenosises will be noted if there were 30% of weeds with APG (APRG, APSG) level 0.5 in case of young-soboliferous-rhizomatous type of infestation. This was confirmed by the results of regression analysis with the level of multiple regression coefficient (R) in the range of 0.555–0.688 ($p < 0.05$) in the system of comparing the frequency of appearance (F) (the resulting trait) and the studied types of allopathic potential (APG (Petri dish bioassays), APG (Soil bioassays), APRG, APSG).

4. Oilseed radish as a multidisciplinary bioenergy crop has demonstrated high biogas and biomethane potential with the possibility of long-term use and biomass harvesting in a wide range of phenological phases.From the point of view of the potential share of methane yield in combination with biogas productivity for the phenological phase of budding (BBCH 50–53) and flowering (BBCH 64–67) with the subsequent process of silage fermentation, the variant of the first sowing term with the level of biochemical methane potential (BMPGomp), respectively, 304.94 and 344.13 LN $kg^{-1}{}_{ODM}$, specific methane yield (SMY) 296.91 and 319.66 LN $kg^{-1}{}_{ODM}$ with a maximum specific methane production rate (R_m) 27.88 and 33.74 LN $kg^{-1}{}_{ODM}$ d^{-1} . For the phenological phase of the green pod (BBCH 73–75), the variant of the fourth sowing term (summer term as a possible option for intermediate cultivation of oilseed radish in crop rotation) with the corresponding parameters was determined as expedient: BMPGomp 287.26 LN $kg^{-1}{}_{ODM}$, SMY 283.18 LN $kg^{-1}{}_{ODM}$ at R_m 29.46 LN $kg^{-1}{}_{ODM}d^{-1}$. The optimal biochemical idiotype of oilseed radish plants was determined in the system of pairwise correlation and multiple regression comparison from the point of view of realization of biomethane potential of the crop when harvesting its biomass in the interphase period of budding–green pod (BBCH 50–75): CP 14–18%DM, CFb 16–20%DM, CA 14–18%DM, CF 3.1–3.2%DM, NfE 48–50%DM at a C/N ratio of 20–22 with the acidity of the subsequent silage-fermented mass at the level of pH 4.6–5.0.

5. Based on comparison of the oil from the seeds of oilseed radish varieties of different breeding, both in terms of the fatty acid composition and its physical and physicochemical properties, this crop should be considered as one of the promising ones for use in the production of multicomponent biofuels. Oil from these varieties, on average, is characterized by a high content of monounsaturated fatty acids (59.69%), especially the highest value of oleic acid (18:1; 33.87%). PU/MU was rather lower – 0.479–0.545 – so the oxidative stability of this oil is high. The other fatty acid ratios (DR – 0.326–0.349, ER – 0.257–0.306, ODR – 0.446–0.487, LDR – 0.418–0.473, S/U – 0.099–0.132) indicate a wide range of potential biofuel use for the oil of this plant species. Particularly valuable in this regard were the varieties ‘Sabina’ and ‘Nika’ with the highest values of oleic acid (18:1; 34.62–34.97%) and an S/U ratio of 0.099–0.102.

The possibility of successful use of oil from oilseed radish is also confirmed on the basis of a comparative analysis of its basic properties with those of other oils common in biofuel production. Among the valuable features are a low level of carbon residue (0.31 wt.%) and low sulphur content (0.0017 wt.%), a high calorific value (37.93 MJ kg^{-1}) and preservation of the main physical and physicochemical parameters of the oil during hightemperature flow (polymerization), especially against the background of its oxypolymerization. The last factor confirms the possibility of successful use of this oil in closed engine systems. However, the low freezing point, high flash point and higher viscosity values are reasons to recommend its use as a component of mixed biofuels. This direction needs additional scientific study.

6. The potential of oil radish in terms of soil rehabilitation and soil restoration in Ukraine is not fully utilized, which requires the inclusion of oil radish as a component of bioorganic, green manure, phytoremediation, phytoremediation and bioenergy technologies in areas subject to anthropogenic and agroecological degradation of soil cover of varying degrees.

7. Oilseed radish should also be considered as a valuable component of agrobiocenoses of territories, providing both a positive balance of nutrients in soils due to natural processes of biorecycling of its biomass and a commodity of the honey and herbal medicine base, which occupies an important ecological niche in the biogeocenosis of many territories and countries.

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