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# EFFECT OF NICKEL IONS ON ECOTOXICOLOGICAL RESPONSES OF THE GREAT RAMSHORN *PLANORBARIUS CORNEUS* ALLOSPECIES (MOLLUSCA: GASTROPODA: PULMONATA: PLANORBIDAE) OF THE UKRAINIAN RIVER NETWORK

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ABSTRACT: This ecotoxicological study analyzed the impact of $Ni^{2+}$ ions in different concentrations on the ecotoxicological and physiological features of the western and eastern vicariant allospecies of the great ramshorn superspecies *Planorbarius corneus* (Linnaeus, 1758) sensu lato in Ukrainian populations from rivers in two different nature-geographic zones: Forest (Polissia) and Forest-Steppe. The two allospecies differed from each other significantly ($p \leq 0.05–0.001$) in their responses to the main ecotoxicological indexes ($LC_0$, $LC_{50}$, $LC_{100}$) in terms of the duration of the latent period, lethal time and mortality rate. By all these indices, the western allospecies had significantly more tolerance than the eastern allospecies. The same was true also for respiratory responses. Under the MPC (maximum permissible concentration) of $Ni^{2+}$ ions in the environment, no changes were registered compared to the control. Increase in toxicant concentration up to 2 MPC was followed by increase in the rate, number, volume and duration of inspirations. At 3 MPC of $Ni^{2+}$, however, the indices of direct diffusive respiration progressively decreased. In all measures, the western allospecies appeared better able to adjust to, and to survive increasing concentrations of $Ni^{2+}$ than that from the east.

KEY WORDS: Gastropoda; differential $Ni^{2+}$; responses; Ukrainian hydrosphere

## INTRODUCTION

The great ramshorn snail *Planorbarius corneus* (Linnaeus, 1758) was, at the beginning of the 21st century, one of the most widespread and abundant gastropod molluscs in Ukrainian fresh water habitats. It is a widespread species, nominally found from the Atlantic to the Urals and beyond. Recent work, however, based on genetic markers (GARBAR 2003, MEZHZHERIN et al. 2005, GARBAR & GARBAR 2006) has shown that *P. corneus* is a superspecies complex, and that in Ukraine there are two vicariant allospecies, western and eastern, significantly differentiated by the centromere indexes of 12th chromosome pair (HARBAR et al. 2021). These allospecies are also distinguished by shell size, and by numerous conchological and anatomical variables (GARBAR 2003, BABYCH et al. 2021). The two allospecies are geographically separated by a zone approximately 100 km wide following the Dnipro river channel.

Toxicological studies by HARBAR et al. (2021) revealed the impact of different $Ni^{2+}$ ions concentrations (0.001–1000 mg/L) on the responses of the two allospecies of *P. corneus*. The indices of mortality,

mean lethal time, adaptation coefficients of pulmonary and diffusive respiration appeared significantly different between allospecies ($p \leq 0.05–0.001$). In all cases, the eastern allospecies was more sensitive and suffered greater mortality than the western one at any given $Ni^{2+}$ concentration.

Heavy metal pollution in Ukrainian rivers has increased greatly in recent decades, threatening the functioning of freshwater ecosystems (BABYCH 2022, BABYCH et al. 2022). While very low concentrations of some heavy metals are needed for by many freshwater animals, including molluscs (PIWONI-PIÓREWICZ et al. 2017, SANTORE et al. 2021, BABYCH et al. 2021, GANDZYURA et al. 2021, UVAYEVA et al. 2022), increased concentrations become toxic (BRIX et al. 2017, PETERS et al. 2019, PINKINA et al. 2022).

$Ni^{2+}$ is among these heavy metals. In very low concentrations it is a necessary component, both in the process of hematopoiesis and of reproduction (ROMANENKO 2001). At higher concentrations, however, toxic effects become important. These may be complex. While very high concentrations (11.4 mg/L) are lethal to molluscs after 96 hours exposure, the effects are influenced by the age of the molluscs (HARANADHA et al. 2011), and by the hydrochemical conditions of environment, level of food consumption, their overall physiological state and genetic features of individuals (OROS & GOMOIU 2010, ZUYKOV et al. 2013).

The aim of the present study is to compare the ecotoxicological effects of increasing concentrations of $Ni^{2+}$ ions on the vicariant allospecies of *P. corneus*.

## MATERIAL AND METHODS

The positions of the sampling stations in relation to the biogeography of Ukraine is shown in Fig. 1. A sample (310 specimens) of the western allospecies was made in the Sapohivka river (Prypiat basin) near the Miropol settlement (50°6'27"N, 27°41'45"E, Right Bank Ukraine, Fig. 2), and a sample of 302 of the eastern allospecies from the Psel river near Bilotserkivka village (49°40'17"N, 33°45'39"E) (Fig. 3). Snails were collected by hand from four types of biotopes in each: shallow water of 5–7 cm depth, with bottom covered

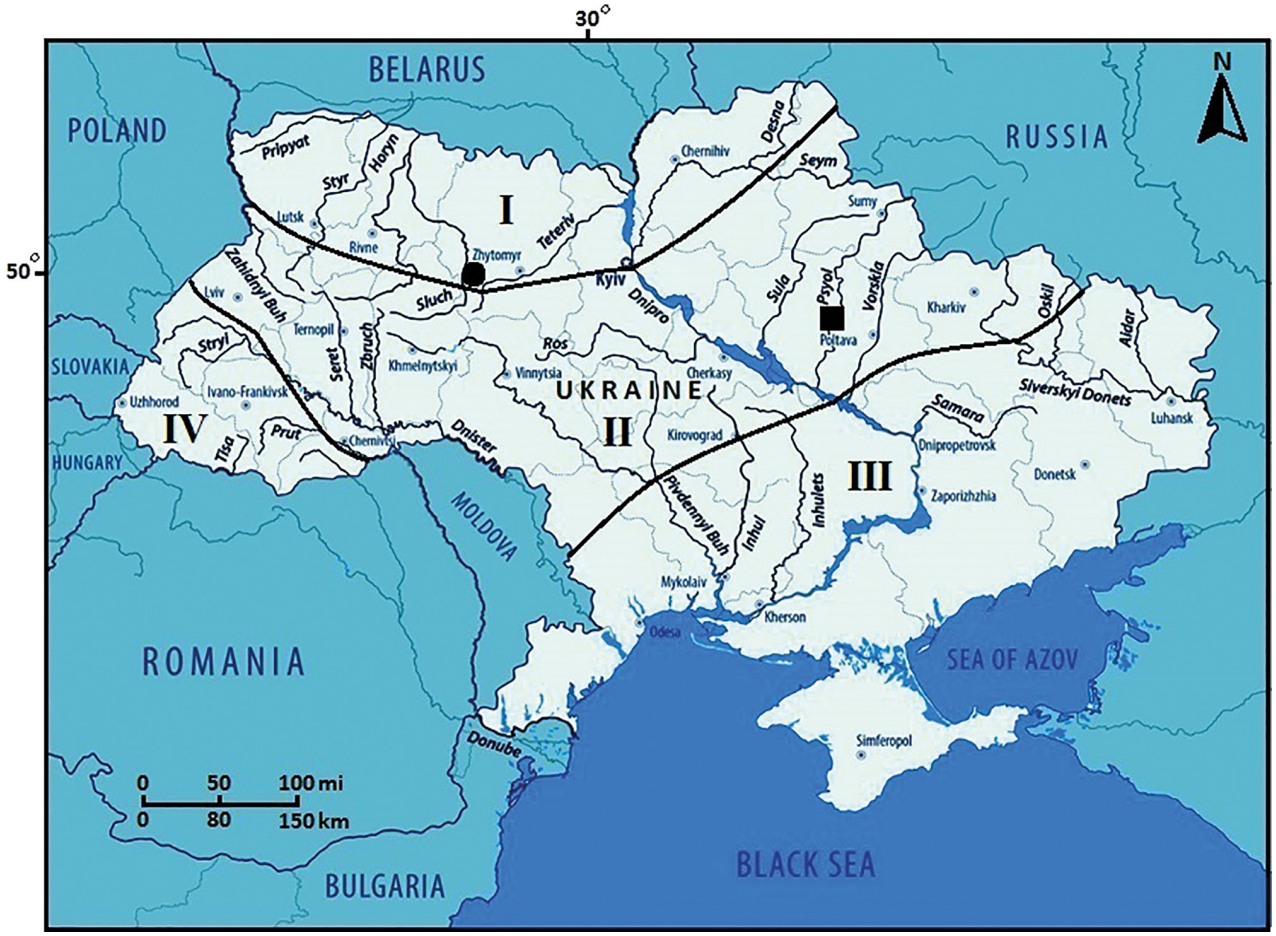


Fig. 1. Map showing the typical localities of *Planorbarius corneus* s. lato allospecies: I – Polissia; II – Forest-Steppe; III – Steppe; IV – Carpathian mountain region; black circle – "western"; black squares – "eastern"



Figs 2–3. Habitats of great ramshorn *Planorbarius corneus* s. lato: 2 – Sapohivka river (Miropol village, Zhytomyr region); 3 – Psel river (Bilotserkivka village, Poltava region)

by *Cladophora* sp. and with weak, variable flow; sites thickly covered with hemi-immersed water plants (*Typha* sp., *Scirpus* sp.) and depth of 15–20 cm, with unnoticeable flow; off the coast at 1–1.25 m depth with powerful development of soft-leaved plants (*Myriophyllum* sp., *Nymphaea* sp., *Lemna* sp.); in the benthic zone, with the bottom covered by plant detritus, and with 0.1–1 m/s flow. Species/allospecies identification was determined on conchological characters, following GARBAR (2003), MEZHZHERIN et al. (2005) and GARBAR & GARBAR (2006).

In the laboratory, the snails were subject to a 15-day period of acclimation in aquariums of 30 l volume at a density of 5 snails/L. Water temperature was maintained at 20–23 °C, pH at 7.3–7.8, and oxygenation at 7.6–8.6 $O_2$ mg/L. The water was changed each day, and food, *Cladophora* sp. and *Myriophyllum spicatum* L., collected in the sampling sites, was renewed daily.

The first toxicological experiment (Tables 1–5) was conducted by the standard method (BABYCH et al. 2022, 2023): aquarium volume – 100 L, water temperature – 20–23 °C, pH – 7.3–7.8, oxygenation – 7.6–8.9 $O_2$ mg/L. Toxicant – $NiCl_2 \cdot 6\ H_2O$ (p.a.) in concentrations between 0.001–100 in mg/L (per cation), expressed also in terms of MPC – maximum permissible concentration. In each of the experimental groups (Tables 1–5) there were 20 specimens of molluscs. Observations were made at 10, 30 min, 1, 2, 4, 6, 24, 48 hours after commencement. Renewing of environments – each day. The impact of toxicant on the molluscs was estimated by the visual observations of changes in their behavior, registering the integrity of the epithelial body covering, its level and functioning, locomotory activity, and intensity of their feeding and digestive processes.

The second toxicological experiment (Table 6) examined the impact of different concentrations of $Ni^{2+}$ ions on the pulmonary and surface respiration of ramshorn allospecies, following the methods of BABYCH et al. (2023).

Analysis of results used the standard methods given by HILL & LEWICKI (2007) identifying any differences between western and eastern allospecies, using statistically significant differences at the $p<0.05$ and $p<0.001$ levels.

Table 1. The main toxicological characteristics of *P. corneus* s. lato allospecies under the exposure of $Ni^{2+}$ (48 hours)

| Indicator, mg/L | „Western" allospecies | „Eastern" allospecies |
|---|---|---|
| Threshold concentration | 0.01 | 0.001 |
| $LC_0$ | 0.1 | 0.03 |
| $LC_{50}$* | 20 | 3 |
| $LC_{100}$ | 50 | 10 |

$LC_0$ – the highest concentration which caused no mortality of molluscs.
$LC_{50}$ – lethal concentration which caused in accordance 50% mortality of molluscs (* set graphically).
$LC_{100}$ – lethal concentration which caused in accordance 100% mortality of molluscs.

Table 2. Latent period (hours) of *P. corneus* s. lato allospecies under the exposure of $Ni^{2+}$

| Concentration, mg/L | "Western" allospecies | "Eastern" allospecies |
|---|---|---|
| | M±SE | M±SE |
| 0.001 | 25.5±1.16 | 21.3±1.24* |
| 0.01 | 21.2±1.23 | 18.1±1.05* |
| 0.1 | 17.5±1.03 | 13.5±1.17* |
| 1.0 | 2.1±1.12 | 1.4±1.28 |
| 10 | 1.1±1.08 | 0.6±1.15 |
| 100 | 0.1±0.98 | 0.04±1.11 |

* – statistically significant differences ($p\leq0.05$) between *P. corneus* s. lato allospecies.

Table 3. Mortality (%) of *P. corneus* s. lato allospecies under the exposure of $Ni^{2+}$ (48 hours)

| Concentration, mg/L | „Western" allospecies | „Eastern" allospecies |
|---|---|---|
| 0.0001 | 0 | 0 |
| 0.001 | 0 | 0 |
| 0.01 | 0 | 0 |
| 0.1 | 0 | 20 |
| 1.0 | 20 | 50 |
| 10 | 80 | 100 |
| 100 | 100 | 100 |
| 1,000 | 100 | 100 |

Table 4. Time-to-death (hours) of *P. corneus* s. lato allospecies under the exposure of $Ni^{2+}$

| Concentration, mg/L | „Western" allospecies | „Eastern" allospecies |
|---|---|---|
| | M±SE | M±SE |
| 0.01 | 0 | 0 |
| 0.1 | 48.3±1.13 | 39.3±1.18* |
| 1.0 | 29.1±1.12 | 18.2±1.02** |
| 10 | 8.1±1.23 | 5.1±1.11 |
| 100 | 2.1±1.13 | 0.5±0.02* |

* – statistically significant differences ($p\leq0.05$) between *P. corneus* s. lato allospecies.

Table 5. Rating of $Ni^{2+}$ concentrations (mg/L) according to the effect on *P. corneus* s. lato allospecies

| Subthreshold | Sublethal | Chronic lethal | Acutely lethal |
|---|---|---|---|
| „Western" allospecies | | | |
| 0.01 and lower | 0.1–2 | 6–13 | 10–40 |
| „Eastern" allospecies | | | |
| $10^{-4}$ and lower | 0.001–0.01 | 0.1–0.4 | 1–10 |

## RESULTS

The study of the impact of the set of different $Ni^{2+}$ concentrations on the main toxicological and some physiological indexes of *P. corneus* sensu lato allospecies established (Tables 1 and 6) that all of them were higher in "western" allospecies that in "eastern" allospecies ($p \leq 0.05$–$0.001$). This confirms the higher level of viability of "western" allospecies: it has a longer latent period (Table 2, $p \leq 0.05$), and lethality at the higher doses of toxicants (Table 3) took longer to occur (Table 4, $p \leq 0.05$).

It was also established that the range of endurance (mg/L) of "western" allospecies under the impact of sub-threshold, sub-lethal, chronic lethal and acute lethal $Ni^{2+}$concentrations exceeded those of "eastern" allospecies (Table 5). The data in Table 5 indicates the higher level of sensitivity and lower level of endurance in "eastern" allospecies concerning all used toxicant concentrations.

The data in Table 6 proves the more intensive duration of pulmonary as opposed to surface diffusive respiration in the individuals of "western" allospecies comparing to "eastern" allospecies ($p \leq 0.05$–$0.001$).

Table 6. The impact of $Ni^{2+}$ in different concentration on indexes of lung and direct diffusive respiration of *P. corneus* s. lato allospecies

| Toxicant concentration | n | Indexes of lung respiration | | | | Index of direct diffusive respiration, h |
|---|---|---|---|---|---|---|
| | | Daily number of inspirations | Interval between inspirations, min | Duration of inspiration, min | Volume of inspiration, number of bubbles | |
| | | M±SE | M±SE | M±SE | M±SE | M±SE |
| "Western" allospecies (Sapohivka river, Miropol) | | | | | | |
| Control | 20 | 12.99±1.17 | 47.98±1.16 | 16.99±1.38 | 14.95±1.27 | 42.82±2.83 |
| 0.5 MPC | 20 | 13.06±1.13 | 46.95±1.14 | 19.04±1.11 | 15.08±1.23 | 44.94±2.59 |
| 1.0 MPC | 19 | 14.78±1.20 | 41.65±1.15* | 21.18±1.17* | 19.76±1.10* | 47.51±4.09* |
| 2.0 MPC | 19 | 16.70±1.18* | 35.21±1.27** | 24.09±1.11** | 25.68±1.18** | 32.09±3.40** |
| 3.0 MPC | 18 | 9.51±1.09* | 63.11±1.18** | 11.06±1.13** | 7.95±1.15** | 17.46±2.13** |
| "Eastern" allospecies (Psel river, Bilocerkivca) | | | | | | |
| Control | 20 | 10.13±1.01 | 57.71±1.19 | 14.76±1.18 | 12.43±1.16 | 37.78±2.74 |
| 0.5 MPC | 20 | 11.34±1.26 | 55.88±1.16 | 16.17±1.20 | 16.09±1.11 | 42.21±2.12 |
| 1.0 MPC | 19 | 12.25±1.21 | 55.14±1.31* | 18.60±1.51* | 22.05±1.06** | 43.48±2.46* |
| 2.0 MPC | 18 | 14.09±1.22* | 43.61±1.14** | 22.05±1.07** | 38.33±2.07** | 31.04±2.05** |
| 3.0 MPC | 19 | 5.03±1.14** | 96.01±1.15** | 8.31±1.03** | 4.27±1.08** | 12.01±1.19** |

n – number of individuals studied; MPC – maximum permissible concentration of ions in the water; M±SE – mean value of index and its standard error; * – statistically significant differences ($p \leq 0.05$); ** – highly significant differences ($p \leq 0.001$).

## DISCUSSION

Burning the deposits of fossil energy sources, disposing the wastes of coal and oil refining industry, and the emissions of Ni-Cd batteries production into the hydrosphere components are the main modern sources of Earth freshwater ecosystems pollution by nickel and compounds, and their harmful impact on the hybrobiota (El-Enany & Issa 2000, Binet et al. 2018, Wang et al. 2020). Average yearly emission of $Ni^{2+}$ into the atmosphere is $55.65 \times 10^3$ kg, into the aquatic ecosystems – $113 \times 10^6$ kg, and into the soil – $416.5 \times 10^6$ kg (Shukla et al. 2009).

$Ni^{2+}$ ions enter aquatic molluscs mainly from the environment through the body's ectodermal epithelial coverings, and much less from their plant food (Wong & Pak 2004, Oros & Gomoiu 2010, Yevtushenko & Dudnyk 2019). These ions accumulate first in the hepatopancreas, subsequently distributed among different organs and tissues, maintained by the ongoing circulation of hemolymph.

$Ni^{2+}$, in very low concentrations, is essential to freshwater gastropods to maintain hematopoiesis at the optimal level (Romanenko 2001), which is one of the crucial conditions for maintenance of their internal homeostasis, and hence their viability and maximum population size and density (Afanasyev & Grodzinsky 2004, Baeva & Chernikh 2020). Exceeding the optimal $Ni^{2+}$ ion concentrations in the water, however, is progressively more lethal for them (Babych & Pinkina 2021, Harbar et al. 2021). The maximal permitted concentration of $Ni^{2+}$

for hydrobionts from Ukrainian river network is 0.01 mg/L (Decree of the Cabinet of Ministers of Ukraine 2013). Exceeding this concentration drives a sequence of phasic pathological processes, whose duration is divided into 1 to 5 phases (dependent on the dose acquired), each having a characteristic set of symptoms. Under the MPC of $Ni^{2+}$ in the environment (0.01 mg/L) the experimental molluscs developed the first intoxication phase – latent, without symptoms, the most secure and the longest. Under 2 MPC, the latent phase changed into the stimulation phase, an increase in physiological activity that maintained viability in experimental conditions. However, the impact of these ions under 3 MPC induced a rapid onset of the three final phases of intoxication – the first and longest being depressive (linked with progressive decrease of all the vital processes), followed by acceleration of these in the sub-lethal phase, and terminating in death.

The "eastern" allospecies moved through these phases more rapidly in relation to ionic concentrations than the "western" allospecies, and its traits developed earlier. The "western" allospecies has evolved more tolerance. The index of direct diffusive respiration in the "western" allospecies is higher than in the "eastern" one when pulmonary respiration is prevented ($p \leq 0.05$–$0.001$); the total amount of oxygen consumed by these molluscs during diffusive surface respiration is almost the same as consumed during pulmonary respiration (Babych 2022). The data in Table 6 also indicates that pulmonary respiration in "western" allospecies is more effective comparing to that in "eastern" allospecies; the "western" allospecies had a greater number of performed "inspirations" (daily) and their duration and volume along with much shorter intervals between them follow the same pattern ($p \leq 0.05$–$0.001$).

It is noteworthy that our results supplement those obtained earlier by Harbar et al. (2021). However we collected material in different period of year. The studied molluscs were studied in different parameters, therefore received different results. This comparison of "western" and "eastern" allospecies of *P. corneus* sensu lato in terms of their response to increasing concentrations of $Ni^{2+}$ raises the question of how such differences arose. A possible reason for such a difference may lie in the different nature-geographic conditions in which they have lived (Logvinov & Shcherban 1984, Stadnychenko et al. 2020). These conditions are much harder for "eastern" allospecies, which is distributed in drought climate of the Left-Bank Ukraine and the extreme South of Ukraine's Steppe Zone.

## REFERENCES


Afanasyev S. A., Grodzinsky M. D. 2004. Methodology for assessing environmental risks arising from the impact of pollution sources on water bodies. IB, Kyiv.

Babych Yu. V. 2022. The impact of $Zn^{2+}$ in water environment on the diurnal respiration cyclicality of *Planorbarius corneus* s. l. (Mollusca, Gastropoda, Planorbidae) allospecies. Scientific Issues of TNPU. Series: Biology 82: 28–36. [in Ukrainian] https://doi.org/10.25128/2078-2357.22.3.5

Babych Yu., Kyrychuk G., Romaniuk R., Stadnychenko A., Uvayeva O. 2023. Impact of some mineral fertilizers on the pulmonary and direct surface respiration of the allospecies of *Planorbarius corneus* superspecies (Gastropoda: Pulmonata: Planorbidae) from the Ukrainian water bodies. Folia Malacologica 31: 9–18. https://doi.org/10.12657/folmal.031.002

Babych Yu., Pinkina T. 2021. Influence of heavy metal ions on ecotoxicological indicators of *Planorbarius corneus* (Mollusca, Gastropoda, Pulmonata, Bulinidae). Visnyk of Lviv University. Biological series 81: 76–83. [in Ukrainian] https://doi.org/10.30970/vlubs.2021.84.07

Babych Yu., Romaniuk R., Stadnychenko A., Uvayeva O. 2022. Effect of zinc ions on the lung and cutaneous diffusive respiration of the great ramshorn *Planorbarius corneus* allospecies (Mollusca: Gastropoda: Pulmonata: Planorbidae) of the Ukrainian river network. Folia Malacologica 30: 135–142. https://doi.org/10.12657/folmal.030.020

Babych Yu., Uvayeva O., Stadnychenko A. 2021. Food preferences of the great ramshorn *Planorbarius corneus* (Linnaeus, 1758) allospecies (Mollusca: Gastropoda: Planorbidae) from the Ukrainian river system. Folia Malacologica 29: 204–211. https://doi.org/10.12657/folmal.029.023

Baeva Yu. I., Chernikh N. A. 2020. Assessment of the ecological state of the coastal waters of the Black Sea by bioindication methods. Water and Ecology 83: 22–31. [in Ukrainian]

Binet M. T., Adams M. S., Gissi F., Golding L. A., Schlekat C. E., Garman E. R., Merrington G., Staubera J. L. 2018. Toxicity of nickel to tropical freshwater and sediment biota: A critical literature review and gap analysis. Environmental Toxicology and Chemistry 37: 293–317. https://doi.org/10.1002/etc.3988

Brix K. V., Schlekat C. E., Garman E. R. 2017. The mechanisms of nickel toxicity in aquatic environments: An adverse outcome pathway analysis. Environmental Toxicology and Chemistry 36: 1128–1137. https://doi.org/10.1002/etc.3706

Decree of the Cabinet of Ministers of Ukraine 2013. Rules for the protection of surface waters from pollution by return waters. The Cabinet of Ministers, Kyiv. [in Ukrainian]

EL-ENANY A. E., ISSA A. A. 2000. Cyanobacteria as a biosorbent of heavy metals in sewage water. Environmental Toxicology and Pharmacology 8: 95–101. https://doi.org/10.1016/s1382-6689(99)00037-x

GANDZYURA V. P., KLYMENKO M. O., BYEDUNKOVA O. O. 2021. Biosystems in a toxic environment. The National University of Water and Environmental Engineering, Rivne.

GARBAR D. A. 2003. Genus *Planorbarius* (Gastropoda, Pulmonata, Bulinidae) in the fauna of Ukraine. Proceedings of the State Natural History Museum 18: 123–126. [in Ukrainian]

GARBAR A., GARBAR D. 2006. Genogeographical approach to the taxonomy of molluscs on the example of the allospecies complex of *Planorbarius corneus* s. l. Ecological-physiological and faunal aspects of malacological research the role of molluscs in bioindication of the state of the environment 2: 57–59. [in Russian]

HARANADHA REDDY M., VENKATA REDDY M., RADHAKRISHNAIAH K. 2011. Evaluation of nickel toxicity in freshwater snail, *Pila globosa* (Swainson) in relation to body size. Nature Environment and Pollution Technology 10: 229–232.

HARBAR O., HARBAR D., STADNYCHENKO A., BABYCH Y. 2021. Ecotoxicological responses of two *Planorbarius corneus* s. lato (Mollusca, Gastropoda) allospecies to exposure of heavy metals. International Journal of Aquatic Biology 9: 423–431. https://doi.org/10.22034/ijab.v9i6.1356

HILL T., LEWICKI P. 2007. Statistics. Methods and Applications. StatSoft, Tulsa.

LOGVINOV K. T., SHCHERBAN M. I. 1984. Nature of the Ukrainian SSR. Climate. Naukova Dumka, Kyiv, 113–145. [in Russian]

MEZHZHERIN S., GARBAR D., GARBAR A. 2005. Systematic structure of the *Planorbarius corneus* s. l. complex (Gastropoda, Pulmonata): analysis of allozyme markers and morphometric traits. Vestnik Zoologii 39: 11–17. [in Russian] http://eprints.zu.edu.ua/id/eprint/8961

OROS A., GOMOIU M.-T. 2010. Comparative data on the accumulation of five heavy metals (cadmium, chromium, copper, nickel, lead) in some marine species (molluscs, fish) from the Romanian sector of the Black Sea. Cercetari Marine 39: 89–108.

PETERS A., MERRINGTON G., LEVERETT D., WILSON I., SCHLEKAT C., GARMAN E. 2019. Comparison of the chronic toxicity of nickel to temperate and tropical freshwater species. Environmental Toxicology and Chemistry 38: 1211–1220. https://doi.org/10.1002/etc.4384

PINKINA T., ZYMAROIEVA A., FEDONIUK T., PAZYCH V. 2022. The growth characteristics and survival rates of great pond snail (*Lymnaea stagnalis* L.) juvenile under the heavy metal impact. IOP Conference Series: Earth and Environmental Science 1049: 12074. https://doi.org/10.1088/1755-1315/1049/1/012074

PIWONI-PIÓREWICZ A., KUKLIŃSKI P., STREKOPYTOV S., HUMPHREYS-WILLIAMS E., NAJORKA J., IGLIKOWSKA A. 2017. Size effect on the mineralogy and chemistry of *Mytilus trossulus* shells from the southern Baltic Sea: implications for environmental monitoring. Environmental Monitoring and Assessment 189:197. https://doi.org/10.1007/s10661-017-5901-y

ROMANENKO V. D. 2001. Fundamentals of hydroecology. Oberehy, Kyiv. [in Ukrainian]

SANTORE R. C., CROTEAU K., RYAN A. C., SCHLEKAT C., MIDDLETON E., GARMAN E., HOANG T. 2021. A review of water quality factors that affect nickel bioavailability to aquatic organisms: Refinement of the biotic ligand model for nickel in acute and chronic exposures. Environmental Toxicology and Chemistry 40: 2121–2134. https://doi.org/10.1002/etc.5109

SHUKLA M. K., TRIPATHI R. D., SHARMA N., DWIVEDI S., MISHRA S., SINGH R., SHUKLA O. P., RAI U. N. 2009. Responses of cyanobacterium *Anabaena doliolum* during nickel stress. Journal of Environmental Biology 30: 871–876.

STADNYCHENKO A. P., BABYCH YU. V., GYRYN V. K. 2020. Spatial distribution of *Planorbarius corneus* (Linnaeus, 1758) populations in the hydronetwork of Ukraine in connection with modern global climatic changes in environmental conditions. Current issues of biological science. Nizhyn Mykola Gogol State University, Nizhyn, pp. 96–98. [in Ukrainian]

UVAYEVA O. I., STADNYCHENKO A. P., BABYCH YU. V., ANDRIYCHUK T. V., MAKSYMENKO YU. V., VYSKUSHENKO D. A., IGNATENKO O. O., PINKINA T. V. 2022. Influence of some heavy metals to the pulmonary and direct diffusive respiration of the great ramshorn *Planorbarius corneus* allospecies (Mollusca: Gastropoda: Planorbidae) from the Ukrainian river system. Ecologica Montenegrina 52: 57–67. https://doi.org/10.37828/em.2022.52.9

WANG Z., YEUNG K. W. Y., ZHOU G.-J., YUNG M. M. N., SCHLEKAT C. E., GARMAN E. R., GISSI F., STAUBER J. L., MIDDLETON E. T., WANG Y. L. L., LEUNG K. M. Y. 2020. Acute and chronic toxicity of nickel on freshwater and marine tropical aquatic organisms. Ecotoxicology and Environmental Safety 206: 111373. https://doi.org/10.1016/j.ecoenv.2020.111373

WONG C. K., PAK A. P. 2004. Acute and subchronic toxicity of the heavy metals copper, chromium, nickel and zinc, individually and in mixture, to the freshwater copepod *Mesocyclops pehpeiensis*. Bulletin of Environmental Contamination and Toxicology 73: 190–196. https://doi.org/10.1007/s00128-004-0412-2

YEVTUSHENKO M. YU., DUDNYK S. V. 2019. Water toxicology. OLDI-PLUS, Kherson. [in Ukrainian]

ZUYKOV M., PELLETIER E., HARPER D. A. 2013. Bivalve mollusks in metal pollution studies: from bioaccumulation to biomonitoring. Chemosphere 93: 201–208. https://doi.org/10.1016/j.chemosphere.2013.05.001

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