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NEW MAGNETOSENSITIVE NANOSTRUCTURED MATERIALS: CURRENT STATUS AND RESEARCH PROSPECTS

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The review analyzes and summarizes the results of research covering a wide range of topical issues in chemistry, physics, medicine (in particular oncology), photopharmacology, biology, and ecology.

Examples of promising developments for practical use are considered, related to the chemical design of multi-level core-shell nanocomposites with the functions of medical and biological nanorobots. An example of a structural model of a nanocomposite is given, which includes four hierarchical levels, namely: core – a single-domain magnetite nanoparticle (1), shell – chemically modified surface of the core (2), immobilized biofunctionalized layer (3) and nanocapsule (4).

A new generation of magnetic adsorbents with different surface properties for medical, technical, technological, and environmental applications has been developed and presented. New magnetic fluids based on physiological solution, containing magnetosensitive multifunctional nanocomposites with relevant antitumor drugs and antibodies have been developed. A nanotechnological basis has been developed for minimally invasive methods of photodynamic antitumor therapy and non-invasive controlled pharmacological effects of a given direction on biological cell systems, etc.

The identified features of the developed magnetic fluids include the synergistic antitumor action of their active components and the overcoming of drug resistance in malignant cells and tumors. The example of MR based on physiological fluid, magnetite, and cisplatin shows that, according to general and biochemical blood indicators, it does not have a more toxic effect on the body compared to the official antitumor drug cisplatin in traditional use.

X-ray luminescent nanostructures can be used in photodynamic antitumor therapy as part of magnetite-lanthanum fluoride nanocomposites for controlled targeted delivery of a photosensitive pharmacological drug and its fixation in the body, while those integrated into a bioactive ceramic medium can be used in bone surgery complicated by tumor processes.

The promising prospects of new effective protective materials capable of absorbing electromagnetic radiation in specified spectral ranges for use in electronics and combating electromagnetic smog are demonstrated, as well as the creation of coatings active in the infrared and ultra-high frequency ranges of the spectrum. Broadband absorption and transmission in this case are important factors determining the operational suitability of materials.

***Keywords**: nanostructures, core-shell nanocomposites, nanorobot functions, magnetic adsorbents, antitumor therapy, photopharmacology, magnetic fluids, interaction with electromagnetic radiation*

INTRODUCTION

The problem of creating molecular and nanoscale structures, which in terms of their functional capabilities were defined as molecular machines, nanomotors, nanorobots, *etc*., capable of performing a range of practical chemical, technological, biological, or medical actions at the atomic, molecular, and genetic levels [1–9], has not lost its relevance to this day. Reviews [10, 11] summarize the achievements and analyze the directions of development of scientific approaches in the field of creating nanorobots with extended capabilities that can perform various tasks and have been the focus of significant research interest. In recent years, physical and chemical methods of their manufacture, in particular, using self-organization, have been at the heart of the implementation of certain useful functions. Therefore, researchers are paying considerable attention to the design of nanorobots in order to facilitate their introduction into clinical practice and fully realize their potential in biomedical research and healthcare.

It should be noted that the practical application of these nano- and molecular self-propelled structures for purposes such as targeted drug delivery or other useful functions remains quite problematic, and research on them is still in the laboratory and preclinical stages.

Therefore, an alternative nanochemical approach used in the work [12], in which Fe_2O_3 magnetic nanoparticles (NPs) encapsulated in a thin silica shell functionalized with fluorescent dyes and LH-RH groups for biotargeting specific cancer cell receptors were synthesized and studied. Such hierarchically structured nanoparticles, defined as “nanoclinics,” were characterized by their capability to enhance the contrast of magnetic resonance and optical imaging in studies of biological effects, as well as to perform targeted local magneto-induced cancer therapy.

The presented nanochemical approach [12] has been successfully developed in the implementation and practical testing of the concept of core-shell nanocomposites (NC) with the functions of medical and biological nanorobots [13]. Namely, recognition of microbiological objects in biological environments; targeted delivery of drugs to target cells and organs and deposition; complex local chemo-, immuno-, neutron capture-, hyperthermic-, photodynamic therapy and real-time diagnostics, detoxification of the body by adsorption of toxins, viral particles, heavy metal ions, *etc*., and their removal using an external magnetic field.

Interest in this topic has increased due to the discovery of the synergistic enhancement of the pharmacological action of official anticancer drugs with the participation of biocompatible magnetite nanoparticles [13], which do not exhibit noticeable cytotoxicity when used independently. Also relevant from a scientific and practical point of view is the phenomenon of broadband absorption of ultra-high frequency (UHF) electromagnetic radiation by media containing NCs with dielectric, magnetic, and conductive losses [14], which may indicate prospects for unique technical applications [15–20], in particular in the field of creating new types of surfaces and coatings with specified electrodynamic properties.

In addition, it is impossible to miss another problem, the solution of which may be related to the use of magnetosensitive nanostructures [21]. Today, the world is faced with the need to improve the effectiveness of drug treatment for serious diseases, in particular, infectious viral and bacterial diseases, malignant cell neoplasms, *etc*. The problem has become extremely acute and relevant throughout the world, and the search for ways to solve it has taken on global significance. A convincing example of this is the COVID-19 coronavirus pandemic. Among the main problems that hinder the effective use of modern antitumor chemotherapy, the most pressing is the development of resistance of malignant cells to chemotherapeutic drugs [22–28], in particular cytostatics. It is known that such drugs, for example, those based on platinum, are characterized by high antitumor activity with a broad spectrum of action and are used in almost all modern clinical chemotherapy regimens. Currently, even the problem of their acute cardio-, nephro-, and neurotoxicity is being solved, in particular, through the use of targeted delivery to specific organs or cells and local therapy methods [13, 21, 29–32], while resistance has become a globally recognized problem since the 1990s [22], which is only getting worse with the emergence of new types and mechanisms [28].

The presented data stimulated the development of a new interdisciplinary scientific and practical direction at the Chuiko Institute of Surface Chemistry of the National Academy of Sciences of Ukraine. The direction is based on the creation of unique multifunctional magneto-sensitive nanostructures and materials aimed at solving a wide range of contemporary problems in chemistry, physics, medicine (in particular oncology), optopharmacology, biology, ecology, technology, *etc*. Therefore, the aim of this work is to review, analyze, and summarize the results of experimental and theoretical studies related to this field, their prospects for development, and practical application.

MULTIFUNCTIONAL NANOCOMPOSITES FOR BIOMEDICAL APPLICATIONS

The task of creating multifunctional nanocomposites for use in biomedical fields requires the development of approaches to the synthesis of new, very complex nanosystems [33–37] that must ensure a strict sequence of unique actions in the human body aimed at achieving a therapeutic result [21]. At the same time, the synthesis conditions should not lead to the loss of magnetic properties and bioactivity of the NP components, and their chemical composition should not cause additional toxic and allergic stress on the body. The magnetic properties of NPs must meet the conditions for the successful delivery of drugs to biological targets and not cause processes of uncontrolled vascular occlusion, embolism, *etc*.

Experimental and theoretical [13] studies at the initial stages of the work are devoted to solving a set of tasks. In particular, our theoretical analysis of the transportation and storage conditions of nanosized magnetosensitive drug carriers in different types of blood vessels, using an external magnetic field, has allowed us to establish criteria for their successful delivery to target organs. We have also estimated the range of field intensity and gradient values and found the relationship between vessel dimensional parameters, blood flow characteristics, and the zone of active field action. The results of the calculations can be useful in creating optimal magnetic systems for the practical implementation of magnetically controlled targeted drug delivery to the therapeutic target.

For example, Fig. 1 shows one of the variants of the proposed scheme for the chemical design of a multilevel hierarchical nanoarchitecture of magnetosensitive NPs with nanorobot functions, which has been developed in accordance with the main chemical and technological stages, implemented and comprehensively tested for functionality. In this model, the core (level 1) performs the functions of a magnetosensitive drug carrier to target organs and cells, a converter of high-frequency magnetic field energy from an external source into thermal energy to create hyperthermic zones, a reactive surface, a contrast agent in MRI diagnostics, *etc*. [13]. The selection and synthesis of magnetosensitive cores of multifunctional NPs for medical and biological applications, which act as drug carriers, is a separate pressing issue that requires comprehensive scientific justification. Therefore, we have developed methods for synthesizing various types of promising magnetosensitive nanomaterials and studied their properties: nanoscale metal particles of Fe, Co, Ni, single-domain ferrites Fe_3O_4, $MnFe_2O_4$, $NiFe_2O_4$, $CoFe_2O_4$, $GdFe_2O_4$, solid solutions in systems $(Fe_{1-x}Mn_x)Fe_2O_4$, $(Fe_{1-x}Ni_x)Fe_2O_4$, $(Fe_{1-x}Co_x)Fe_2O_4$, $(Fe_{1-x}Zn_x)Fe_2O_4$, *etc*. By changing their type and varying their chemical composition, it is possible to meet many requirements that arise when creating NPs with a given set of properties.

$LaF_3:Tb^{3+}$ (Figs. 2, 3 *a*) is characterized by a nearly spherical shape of nanoparticles (D_{av} = 11.17±3.09 nm), while $LaPO_4:Tb^{3+}$ (Figs. 2, 3 *b*) exhibits slight anisotropy in crystal growth, with an average length of L_{av} = 19.92±4.55 nm.

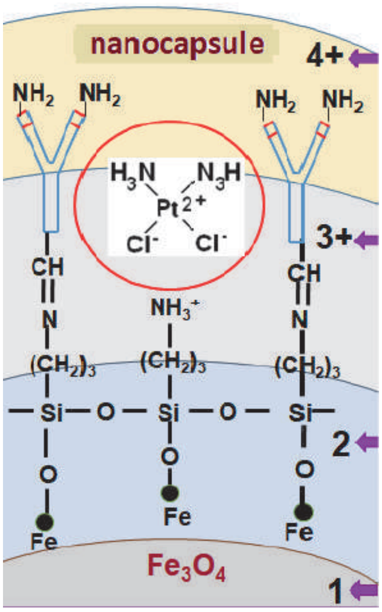
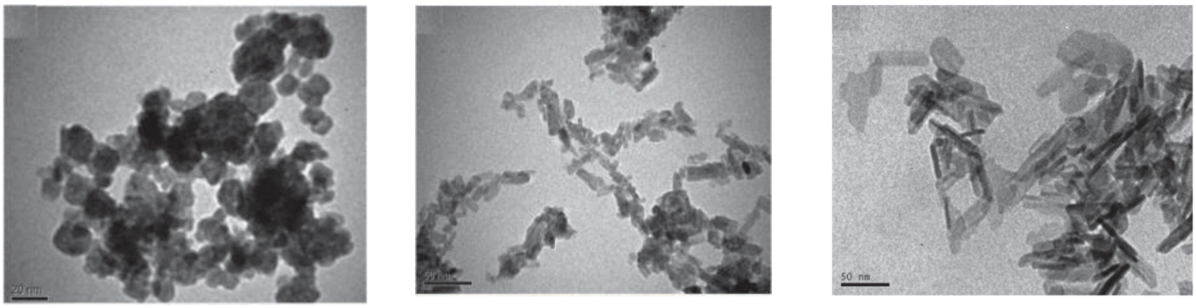


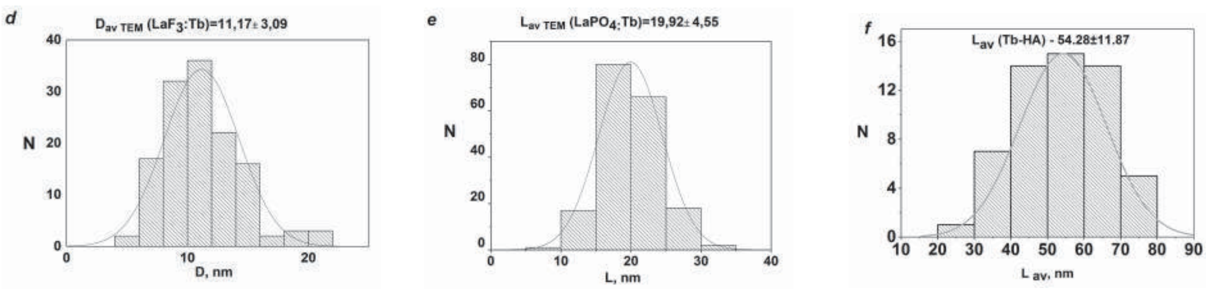
Fig. 1. Structural model of NC type core – multi-level shell: level 1 (8–12 nm), single-domain magnetite; level 2 (1–2 nm); level 3 (1–2 nm); level 4 (1 nm)



a *b* *c*

Fig. 2. TEM images of nanoparticles: *a* – $LaF_3:Tb^{3+}$ (scale bar 20 nm), *b* – $LaPO_4:Tb^{3+}$ (scale bar 50 nm) and *c* – $HA:Tb^{3+}$ (scale bar 50 nm)

For $HA:Tb^{3+}$ crystallites (Fig. 2, 3 *c*), significant growth anisotropy and a rod-like shape are characteristic. On average, the length-to-width ratio for such samples is ≈ 5:1, and the addition of Tb^{3+} does not affect the morphology of nanoparticles at the concentrations used. A similar morphology of $HA:Tb^{3+}$ crystallites was observed by the authors of studies [77–80]. The distribution of nanoparticles by nanorod length, calculated from TEM images (Fig. 3 *c*), shows that their average length L_{av} = 54.28±11.87 nm. It should be noted that the sizes of the synthesized X-ray luminescent nanoparticles meet the criteria of many drug delivery systems [81, 82].



a *b* *c*

Fig. 3. Particle size distribution according to TEM: *a* – LaF_3: Tb^{3+}, *b* – $LaPO_4$: Tb^{3+}, and *c* – HA: Tb^{3+} (note N – number of nanoparticles)

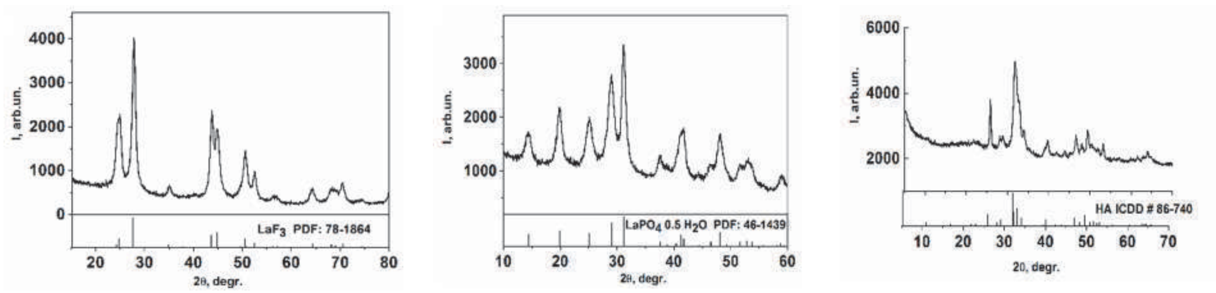
Fig. 4 *a–c* shows the results of X-ray diffraction studies of synthesized samples of NPs LaF_3: Tb^{3+}, $LaPO_4$: Tb^{3+}, and HA: Tb^{3+}. It should be noted that in terms of the angular positions of reflections, shape, width and intensity ratio, the above diffractograms are practically indistinguishable from the diffractograms of the corresponding samples of terbium-doped nanostructures [75].

The results show that under the experimental conditions, fairly perfect LaF_3: Tb^{3+} crystals (Fig. 4 *a*) of hexagonal symmetry, space group P3c1 (ICDD: 78-1864), were formed. According to X-ray diffraction data (ICDD 46-1439), the synthesized $LaPO_4:Tb^{3+}$ sample (Fig. 4 *b*) consists of the $LaPO_4 \cdot 0.5H_2O$ phase (ICDD No. 46-1439) of hexagonal symmetry, space group P3121. All diffraction reflections of $HA:Tb^{3+}$ nanoparticles (Fig. 3 *c*) are well consistent with the diffractograms of hydroxyapatite with a hexagonal structure and space group P63/m (ICDD No.: 86-740). The average crystal size, calculated using the Sherrer formula, is: for LaF_3: Tb^{3+} 10 nm, $LaPO_4$: Tb^{3+} – 14 nm, $HA:Tb^{3+}$ – 20 nm; the corresponding specific surface areas are 103, 100, and 95 m^2/g.

Given the similar sizes of Ca^{2+}, La^{3+}, and Tb^{3+} ions, it can be assumed that Ca^{2+} and La^{3+} ions can be replaced by Tb^{3+} ions in $LaF_3:Tb^{3+}$, $LaPO_4:Tb^{3+}$, and $HA:Tb^{3+}$ samples. Thus, the possibility of replacing divalent calcium with trivalent terbium in the structure of $HA:Tb^{3+}$ has been confirmed by our study of the elemental composition of the samples (Ca/P ratio and

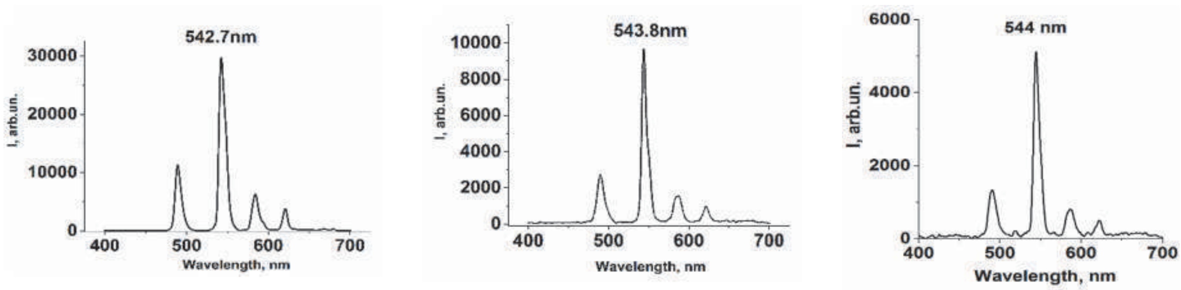
(Ca+Tb)/P ratio), and the inductively coupled plasma atomic emission spectroscopy method (ICPE-9000 device (Shimadzu, Japan)).

Comparing the sizes of the studied nanostructures obtained by TEM studies with XRD data, we can note their correspondence within the margin of error for $LaF_3:Tb^{3+}$ and $LaPO_4:Tb^{3+}$. Quite large differences in size are observed for $HA:Tb^{3+}$ samples, which can be explained by the peculiarities of their crystal structure, in particular, growth anisotropy and high porosity. Thus, studies of $HA:Tb^{3+}$ samples using the low-temperature adsorption-desorption of nitrogen at –196 °C using a NOVA 1200e Surface Area & Pore Size Analyzer (Quantachrome, USA), the specific surface area S $HA:Tb^{3+}$ = 149.2 m^2/g was obtained, and the pore volume was 0.64 cm^3/g.



a *b* *c*

Fig. 4. XRD spectra of nanoparticles: *a* – $LaF_3:Tb^{3+}$, *b* – $LaPO_4:Tb^{3+}$, and *c* – $HA:Tb^{3+}$



a *b* *c*

Fig. 5. Typical X-ray luminescence spectra of nanodispersed samples *a* – $LaF_3:Tb^{3+}$, *b* – $LaPO_4$:Tb Tb^{3+} and *c* – $HA:Tb^{3+}$

Fig. 5 *a–c*, shows typical X-ray luminescence spectra of nanodispersed samples of $LaF_3:Tb^{3+}$, $LaPO_4$: Tb^{3+}, and HA: Tb^{3+} NPs. It can be seen that the spectra show four characteristic bands with maxima at ~ 490, 543, 585, and 622 nm. The most intense band at ~ 543 nm corresponds to the 5D4–7F5 transition of Tb, and the bands at ~ 490, 585, and 624 nm correspond to the 5D4–7F6, 5D4–7F4, and 5D4–7F3 transitions of Tb [84].

The good agreement of the characteristic X-ray luminescence bands and the positions of their maxima may indicate, in particular, that the difference in the dielectric properties of lanthanum fluoride and phosphate matrices and hydroxyapatite under the conditions used for the synthesis of nanoscale particles of $LaF_3:Tb^{3+}$, $LaPO_4:Tb^{3+}$, and $HA:Tb^{3+}$, high amorphization, and defectiveness of the crystal structure of the samples, has little effect on the position of Tb^{3+} energy levels in their forbidden zone. However, these factors can significantly affect the intensity of X-ray luminescence, in particular, due to scattering on defects in the crystal structure. In addition, it is known [54] that water molecules on the surface of the phosphor, in the composition of crystal hydrates, as well as surface hydroxyl groups, can be centers of luminescence quenching.

NEW MR-BASED VECTOR SYSTEMS FOR USE IN ONCOLOGY

The technological scheme for the manufacture of a new magnetically controlled multifunctional antitumor vector system based on magnetic fluids containing the necessary drugs in the NK structure consists of the following stages:

synthesis of the carrier (core); modification of the carrier surface; immobilization of drugs; production of magnetic substance concentrate and its stabilization, completion of shell formation [13, 21].

At each stage of obtaining such vector systems, their physicochemical and magnetic parameters and biological activity were monitored. The optimal values of the dimensional and magnetic characteristics of the magnetic carrier (single-domain magnetite) and the parameters for their standardization have been found [13, 21]. The research results can be used in the development of new magnetically controlled adsorption materials for technical, technological, environmental, and medical-biological purposes, in the production of medical test systems, *etc*.

Temporary technological regulations for the production of the substance “Magnetite U” have been registered, which is a nanoscale single-domain Fe_3O_4 and can be used to create a new generation of multifunctional oncological drugs for targeted delivery and local therapy using combined and complex methods, including chemotherapy, immunotherapy, radiological neutron capture therapy, and others. Temporary technological regulations have also been developed for the production of magnetic fluid [56] based on single-domain magnetite, which may contain CP, DR, CD95 antibody, or HER2.

The antitumor drug “Ferroplat”. The synthesized and studied ML Fe_3O_4@Ol.Na@PEG/CP+FR were used in the creation of a new domestic antitumor drug, Ferroplat, in collaboration with the R.E. Kavetsky Institute of Experimental Pathology, Oncology and Radiobiology of the NAS of Ukraine. The idea behind this drug is to overcome the resistance of malignant tumors to cisplatin by pharmacologically correcting the metabolism of endogenous iron, which is achieved by using an iron-containing nanocomposite and cisplatin [21].

Ferroplat is a conjugate of magnetic fluid with cisplatin. It is a standardized agent for increasing the effectiveness of chemotherapy and overcoming drug resistance of malignant neoplasms and is designed for targeted delivery of cytostatics directly to tumor tissue, which ensures maximum entry into cells and contributes to an increase in the therapeutic effect. Its ability to accumulate selectively in tumors improves the antitumor effect of CP while increasing biological safety. Unlike known chemotherapeutic drugs, ferroplat is more active against tumors resistant to CP and is less toxic to normal cells. It has no analogues in the world. Preclinical trials of ferroplat have been successfully completed.

INTERACTION OF NANOSTRUCTURES WITH ELECTROMAGNETIC RADIATION

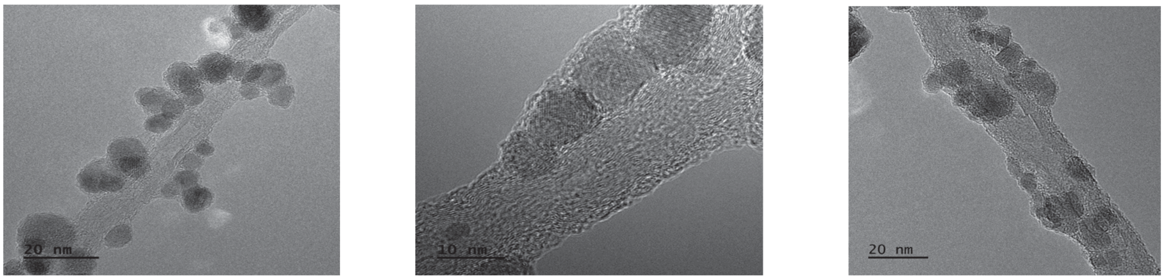
The creation of new effective protective materials capable of absorbing electromagnetic (EM) radiation in specified ranges of the electromagnetic spectrum is an important scientific and technical task closely related to the use of high-tech electronics and the fight against electromagnetic smog. Broadband absorption and broad passband in this case are two important factors that determine the operational suitability of materials. As a rule, such materials and coatings are complex multilayer structures containing components with dielectric, conductive, and magnetic losses of electromagnetic energy [86–95]. Therefore, a certain range of such components interacting with radiation of the corresponding spectral ranges has been synthesized and studied [14].

Within this topic, systems such as polymer matrix – nanodispersed functional filler as a basis for creating composites resistant to external influences are of considerable interest. Various types of composite materials (massive, ultradisperse, film, fibrous, thread) interact effectively with EM and are characterized by additional new unique properties due to interphase interaction of components. An example of the creation of such materials is the development of carbon-iron (Fe/C) nanotubes and nanofibers with magnetic and conductive properties and polypropylene (PP) monofilaments based on them.

In works [94, 95], research was carried out with the aim of synthesizing nanostructures based on manganese ferrite and multi-walled carbon nanotubes (MWCNTs) in polymer composites with increased ability to absorb ultra-high frequency (UHF) radiation (Fig. 6). Polychlorotrifluoroethylene and epoxy resin were used to make the polymer matrices. Effective absorption was found in the 5–20 GHz frequency range, and it was found that for NCs with MWCNTs, the absorption coefficient is 2.5–3 times higher than that for manganese ferrite.

NiCo nanoparticles and nickel-cobalt nanocomposites on graphene nanoplates

(NiCo@GNPs), on highly dispersed silica (NiCo@SiO_2), on unoxidized and oxidized multiwalled nanotubes (NiCo@NMWCNTs, NiCo@OMWCNTs) were synthesized by chemical co-precipitation from solution in the presence of a reducing agent and studied. The size of metal particles reaches 20 nm, and their agglomerates - up to 200 nm. The real and imaginary components of the complex permittivity and magnetic permeability of dispersed nanocomposite systems were determined by ultrahigh-frequency interferometry. The investigated nanostructures are promising for the creation of microwave radiation adsorbers.

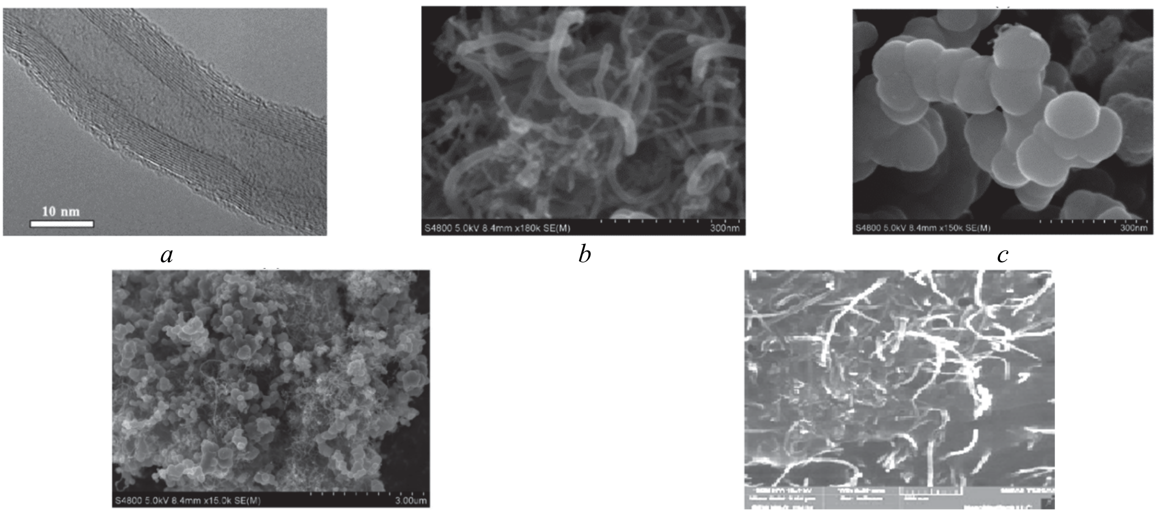


a *b* *c*

Fig. 6. PEM images of synthesized nanocomposites $(NiZn)_{1-x}Mn_xFe_2O_4$/0.05 CNT: x = 0 (*a*), x = 0.5 (*b*) and x = 1 (*c*)

In [14], the manufacture and study of polymer-filled paint coatings active in the ultra-high frequency (UHF) and near-infrared ranges of the spectrum are reported. The advantages of such coatings are their functionality in the UHF and IR ranges, high weather resistance, and manufacturability. Ways to improve them include reducing reflection coefficients and mass-dimensional characteristics, for example, by using core-shell type coatings containing magnetic, dielectric, and electrically conductive components optimized for losses and impedance matching with open space, electromagnetic energy losses, weight characteristics, *etc*. A certain practical approximation to these requirements is provided by Fe_3O_4/Al_2O_3/C core-shell NCs [96].

The aim of work [97] was to study the anisotropy of the electrophysical and mechanical properties of rubber modified with a hybrid filler based on carbon nanotubes and carbon black (Fig. 7) as a function of the content of CNTs and technological parameters of the production process.



a *b* *c*

d *e*

Fig. 7. TEM images of carbon nanotube (*a*); SEM: carbon nanotube agglomeration (*b*), carbon black (*c*), carbon black + carbon nanotubes composite material (*d*), cross-section of the modified rubber sample (*e*)

Significant differences in electrical conductivity (σ) and dielectric constant (ε) in the three perpendicular directions were found for CNT concentrations ranging from 0 to 0.007 wt. %. The highest values of σ and ε were observed in the calendering direction, with slightly lower values in the perpendicular direction. This effect is explained by the orientation of the polymer and CNT molecules along the direction of movement during calendering, as well as the disruption of the cluster structure in the transverse direction. The data obtained are useful in the development of rubber products with optimal electrophysical properties.

In summary, we note that in addition to scientific, practical and methodological, the above studies are also of educational importance, in particular, an important task is to educate students and young professionals of higher qualifications in the relevant specialties. Therefore, these materials are used in the educational process of national universities (NTUU “KPI”, Taras Shevchenko National University of Kyiv), in the preparation of graduate students and doctoral students.

CONCLUSIONS

The current state and prospects for the development and practical application of the most relevant theoretical and experimental author's research in the scientific and practical field of “Multifunctional magnetosensitive nano-structures and materials” are analyzed. Examples of developments related to the following are considered: chemical design of multi-level core-shell nanocomposites with the functions of medical and biological nanorobots; the creation of a new generation of magnetic nanostructured adsorbents with different surface properties for medical, technical, technological, and environmental purposes; the development of a nanotechnological base for modern minimally invasive methods of photodynamic antitumor therapy and non-invasive controlled pharmacological effects of a given direction on biological cell systems; synthesis of new magnetic fluids based on physiological solution containing magnetosensitive multilevel multifunctional NPs with relevant antitumor drugs and antibodies; creation of scientific foundations and manufacture of protective coatings active in specified ranges of the electromagnetic spectrum.

Нові магніточутливі наноструктурні матеріали: стан та перспективи досліджень

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В огляді проаналізовано та узагальнено результати досліджень, що охоплюють широке коло актуальних задач хімії, фізики, медицини (зокрема онкології), фотофармакології, біології, екології.

Розглянуто приклади перспективних для практичного використання розробок, пов’язаних з хімічним конструюванням багаторівневих нанокомпозитів типу ядро-оболонка з функціями медико-біологічних нанороботів. Наведено приклад структурної моделі нанокомпозиту, яка включає чотири ієрархічних рівні, а саме: ядро – однодоменну наночастинку магнетиту (1), оболонку – хімічно модифікувану поверхню ядра (2), іммобілізований біофункціоналізований шар (3) та нанокапсулу (4).

Розроблено та представлено нове покоління магнітних адсорбентів з різною природою поверхні медичного, технічного, технологічного та екологічного призначення; нових магнітних рідин медичного призначення на основі фізіологічного розчину, що містять магніточутливі багаторівневі поліфункціональні нанокомпозити з актуальними протипухлинними лікарськими препаратами та антитілами; розвинено нанотехнологічну базу малоінвазивних методів фотодинамічної протипухлинної терапії та неінвазивного керованого фармакологічного впливу заданого напрямку на біологічні клітинні системи тощо.

До виявлених особливостей розроблених магнітних рідин належать синергізм протипухлинної дії їх активних компонентів та подолання лікарської резистентності злоякісних клітин і пухлин. На прикладі МР на основі *фізіологічної рідини, магнетиту і цисплатину показано, що за загальними і біохімічними показниками крові не створює більш токсичного впливу на організм, в порівнянні з офіційним протипухлинним препаратом цисплатин в традиційному використанні.*

Рентгенолюмінесцентні наноструктури можуть бути використані в фотодинамічній протипухлинній терапії в складі нанокомпозитів магнетит-фторид лантану для контрольованої адресної доставки фоточутливого фармакологічного препарату та фіксації його в організмі, а інтегровані в середовище біоактивної кераміки – застосовані в кістковій хірургії, ускладненій пухлинними процесами.

Показано перспективність нових ефективних захисних матеріалів, здатних поглинати електромагнітне випромінювання в заданих діапазонах спектра для використання в електроніці та боротьбі з електромагнітним смогом; створенні покриттів, активних в інфрачервоному та надвисокочастотному діапазонах спектра. Широкосмугове поглинання та пропускання в цьому випадку є важливими факторами, що визначають експлуатаційну придатність матеріалів.

Ключові слова: *наноструктури, нанокомпозити ядро-оболонка, функції нанороботів, магнітні адсорбенти, протипухлинна терапія, фотофармакологія, магнітні рідини, взаємодія з електромагнітним випромінюванням*

REFERENCES

1. Dey S., Fan C., Gothelf K.V., Li J., Lin C., Liu L., Liu N., Nijenhuis M.A., Saccà B., Simmel F.C. DNA origami. *Nat. Rev. Methods Primers*. 2021. **1**(1): 1.
2. Knappe G.A., Wamhoff E.-C., Bathe M. Functionalizing DNA origami to investigate and interact with biological systems. *Nat. Rev. Mater*. 2022. **8**(2): 123.
3. Geary C., Grossi G., McRae E.K.S., Rothemund P.W.K., Andersen E.S. RNA origami design tools enable cotranscriptional folding of kilobase-sized nanoscaffolds. *Nat. Chem*. 2021. **13**(6): 549.
4. Ibusuki R., Morishita T., Furuta A., Nakayama S., Yoshio M., Kojima H., Oiwa K., Furuta K. Programmable molecular transport achieved by engineering protein motors to move on DNA nanotubes. *Science*. 2022. **375**(6585): 1159.
5. Meyer T.A., Zhang C., Bao G., Ke Y. Programmable assembly of iron oxide nanoparticles using DNA origami. *Nano Lett*. 2020. **20**(4): 2799.
6. Ji T., Shi H., Yang X., Li H., Kaplan D.L., Yeo J., Huang W. Bioinspired Genetic and Chemical Engineering of Protein Hydrogels for Programable Multi-Responsive Actuation. *Adv. Healthcare Mater.* 2024. **13**(27): 2401562.
7. Quan M.C., Mai D.J. Biomolecular Actuators for Soft Robots. *Chem. Rev*. 2025. **125**(10): 4974.
8. Cogal G.C., Das P.K., Karaca G.Y., Bhethanabotla V.R., Oksuz A.U. Fluorescence Detection of miRNA-21 Using Au/Pt Bimetallic Tubular Micromotors Driven by Chemical and Surface Acoustic Wave Forces. *ACS Appl. Bio Mater*. 2021. **4**(11): 7932.
9. Yang Y., Arque X., Patino T., Guillerm V., Blersch P.-R., Perez-Carvajal J., Imaz I., Maspoch D., Sanchez S. Enzyme-Powered Porous Micromotors Built from a Hierarchical Micro- and Mesoporous UiO-Type Metal–Organic Framework. *J. Am. Chem. Soc.* 2020. **142**(50): 20962.
10. Chena G., Zhua F., Gana A.S.J., Mohanb B., Deyc K. K., Xud K., Huanga G., Cuia J., Soloveva A.A., Meia Y. Towards the next generation nanorobots. *Next Nanotechnology*. 2023. **2**: 100019.
11. Tang D., Peng X., Wu S., Tang S. Autonomous Nanorobots as Miniaturized Surgeons for Intracellular Applications. *Nanomaterials*. 2024. **14**(7): 595.
12. Levy L., Sahoo Y., Earl B.J. Nanochemistry: Synthesis and Characterization of Multifunctional Nanoclinics for Biological Applications. *Chem. Mater*. 2002. **14**(9): 3715.
13. Horobets S.V., Horobets O.Iu., Horbyk P.P., Uvarova I.V. *Functional bio- and nanomaterials for medical use*. (Kyiv: Condor, 2018). [in Ukrainian].
14. Horbyk P.P., Makhno S.M., Prokopenko S.L., Lisova O.M., Mazurenko R.V., Turanska S.P., Hunia H.M., Oliinyk K.A., Zhyvets Yu.M. New special materials and coatings that effectively absorb electromagnetic ultra-high frequency and infrared radiation. *Ozbroiennia ta viiskova tekhnika*. 2023. **2**(38): 94. [in Ukrainian].
15. Roco M.C., Williams R.S., Alivisatos P. *Vision for Nanotechnology R&D in the Next Decade*. V. 156 (Dordrecht: Kluwer Academic Publishers, 2002). P. 171.
16. Androshchuk H.O., Yamchuk A.V., Berezniak N.V., Kvasha T.K., Musina L.A., Novitska H.V. *Nanotechnologies in the 21st century: strategic priorities and market approaches to implementation*. (Kyiv: UkrINTEI, 2011). P. 272. [in Ukrainian].

17. Kovtunenko O.L., Bohucharskyi V.V., Sliusar V.I., Fedorov P.M. *Unconventional weapons: Current status and main trends in development. Protection against them.* (Kyiv: TsNDI OVT ZSU, 2004). P. 220. [in Ukrainian].
18. Poplavko Yu.M. *Physics of Dielectrics*. (Kyiv: NTUU “KPI”, 2015). P. 572. [in Ukrainian].
19. Poplavko Yu.M. *Basics of physics of magnetic phenomena in crystals*. (Kyiv: NTUU “KPI”, 2004). P. 227. [in Ukrainian].
20. Borysov O.V. *The basics of solid-state electronics*. (Kyiv: Osvita Ukrainy, 2004). P. 462. [in Ukrainian].
21. Chekhun V.F., Lukianova N.Y., Todor I.M., Storchai D.M., Borikun T.V., Naleskina L.A., Kusyak A.P., Petranovska A.P., Horbyk P.P. Pharmacokinetics and Biological Effects of Ferromagnetic Nanocomposite in Rats with Sensitive and Ddp-Resistant Guerin’s Carcinoma. *Toxicology and Applied Pharmacology Insights*. 2018. **1**(1): 1.
22. Ishikawa T., Wright C.D., Ishizuka H. GS-X pump is functionally overexpressed in cisdiamminedichloroplatinum(II)-resistant human leukemia HL-60 cells and down-regulated by cell differentiation. *J. Biol. Chem.* 1994. **269**(46): 29085.
23. Siddik Z.H. Cisplatin: mode of cytotoxic action and molecular basis of resistance. *Oncogene*. 2003. **22**: 7265.
24. Yang P., Ebbert J.O., Sun Z., Weinshilboum R.M. Role of the glutathione metabolic pathway in lung cancer treatment and prognosis: A review. *J. Clin. Oncol*. 2006. **24**(11): 1761.
25. Stewart D.J. Mechanisms of resistance to cisplatin and carboplatin. *Crit. Rev. Oncol. Hematol*. 2007. **63**(1): 12.
26. Chekhun V.F., Lukyanova N.Yu., Burlaka A.P., Bezdenezhnykh N.A., Shpyleva S.I., Tryndyak V.P., Beland F.A., Pogribny I.P. Iron metabolism disturbances in the MCF-7 human breast cancer cells with acquired resistance to doxorubicin and cisplatin. *Int. J. Oncol.* 2013. **43**: 1481.
27. Shevchenko A.I., Kolesnik A.P., Kadzhoian A.V., Kuzmenko V.A. Chemoresistance factors in non-small cell lung cancer. *Pathologia.* 2016. **1**(36): 4. [in Russian].
28. Zhou J., Kang Y., Chen L., Wang H., Liu J., Zeng S., Yu L. The drug-resistance mechanisms of five platinum-based antitumor agents. *Front. Pharmacol*. 2020. **11**(343): 1.
29. Prylutska S., Politenkova S., Afanasieva K., Korolovych V., Bogutska K., Sivolob A., Skivka L., Evstigneev M., Kostjukov V., Prylutskyy Y., Ritter U. A nanocomplex of C60 fullerene with cisplatin: design, characterization and toxicity. *Beilstein. J. Nanotechnol.* 2017. **8**: 1494.
30. Grebinyk A., Prylutska S., Buchelnikov A., Tverdokhleb N., Grebinyk S., Evstigneev M., Matyshevska O., Cherepanov V., Prylutskyy Y., Yashchuk V., Naumovets A., Ritter U., Dandekar T., Frohme M. C60 fullerene as an effective nanoplatform of alkaloid berberine delivery into leukemic cells. *Pharmaceutics*. 2019. **11**(11): 586.
31. Grebinyk A., Prylutska S., Grebinyk S., Prylutskyy Y., Ritter U., Matyshevska O., Dandekar T., Frohme M. Complexation with C60 fullerene increases doxorubicin efficiency against leukemic cells in vitro. *Nanoscale Res. Lett.* 2019. **14**: 61.
32. Grebinyk A., Prylutska S., Grebinyk S., Ponomarenko S., Virych P., Chumachenko V., Kutsevol N., Prylutskyy Y., Ritter U., Frohme M. Drug delivery with a pH-sensitive star-like dextran-graft polyacrylamide copolymer. *Nanoscale Adv*. 2022. **4**: 5077.
33. *Fabrication and Self-Assembly of Nanobiomaterials. Applications of Nanobiomaterials*. Edited by Grumezescu A.M. (Elsevier Inc., 2016). P. 485.
34. *Surface Chemistry of Nanobiomaterials. Applications of Nanobiomaterials*. Edited by Grumezescu A.M. (Elsevier Inc., 2016). P. 528.
35. Kianfar E. Magnetic nanoparticles in targeted drug delivery: a review. *J. Supercond. Novel Magn.* 2021. **34**(7): 1709.
36. Heidaripour A., Panahi H., Attari G., Jahansooz F. Fabrication of nanocomposite of HAp-SiO_2-Fe_3O_4 suitable for magnetic hyperthermia. *J. Med. Nanomater. Chem*. 2024. **6**(4): 251.
37. Adul-Rasool A.A., Athair D.M., Zaidan H.K., Rheima A.M., Al-Sharify Z.T., Mohammed S.H. 0, 1, 2, 3D nanostructures, types of bulk nanostructured materials, and drug nanocrystals: an overview. *Cancer Treatm. Res. Commun*. 2024, **40**: 100834.
38. Zhou T., Igawa K., Kasai T., Sadahira T., Wang W., Watanabe T., Bekku K., Katayama S., Iwata T., Hanafusa T., Xu A., Araki M., Michiue H., Huang P. The current status and novel advances of boron neutron capture therapy clinical trials. *Am. J. Cancer Res.* 2024. **14**(2): 429.
39. *Advances in boron neutron capture therapy*. (Vienna: IAEA, 2023). P. 416.
40. Jin H., Seldon C., Butkus M., Sauerwein W., Giap H.B. A Review of Boron Neutron Capture Therapy: Its History and Current Challenges. *International Journal of Particle Therapy*. 2022. **9**(1): 71.
41. Crossley E.L., Ching H.Y.V., Ioppolo J.A., Rendina L.M. Chapter 10. Boron and Gadolinium in the Neutron Capture Therapy of Cancer. In Book: Bioinorganic Medicinal Chemistry. *Wiley-VCH Verlag GmbH & Co. KGaA* 2011. P. 283.
42. Photodynamic therapy. National Cancer Institute. 2020.

43. Kianfar E. Magnetic nanoparticles in targeted drug delivery: a review. *J. Supercond. Novel Magn.* 2021. **34**(7): 1709.
44. Mushtaq A., Zhao R., Luo D., Dempsey E., Wang X., Iqbal M.Z., Kong X. Magnetic Hydroxyapatite Nanocomposites: The Advances From Synthesis to Biomedical Applications. *Mater. Des*. 2021. **197**: 109269.
45. Dynnyk O.B., Zalesskyi V.N. Molecular medicine: transformation of intracellular relocation processes of photosensitizers as a reserve for the effectiveness of their photocytotoxic action. *Ukrainskyi medychnyi chasopys*. 2005. **1**(45). [in Ukrainian].
46. Hsieh Y.J., Wu C.C., Chang C.J., Yu J.S. Subcellular localization of Photofrin determines the death phenotype of human epidermoid carcinoma A431 cells triggered by photodynamic therapy: when plasma membranes are the main targets. *J. Cell. Physiol.* 2003. **194**(3): 363.
47. Konan Y.N., Berton M., Guniy R., Alleraam E. En hanced photodynamic activity of meso-tetra(4-hydroxyphenyl)porphyrin by incorporation into sub-200 nm nanoparticles. *Eur. J. Pharm. Sci.* 2003. **18**(3–4): 241.
48. Chatterjee D.K., Fong L.S., Zhang Y. Nanoparticles in photodynamic therapy: an emerging paradigm. *Adv. Drug. Deliv. Rev*. 2008. **60**(15): 1627.
49. Abodunrin T.O., God'shelp O.E., Owoeye F.D., Johnson O.A., Adeyemi O.S. Metal organic frameworks in photodynamic therapy of cancer: functional roles of active Metal centers, integrated and loaded photosensitizers in the ramework. *Mater. Adv.* 2025. **6**. 1554.
50. Niculescu A.-G., Grumezescu A.M. Photodynamic Therapy-An Up-to-Date Review. *Appl. Sci.* 2021. **11**(8): 3626.
51. Shah D., Eroy M., Fakhry J., Moffat A., Fritz K., Cole H.D., Cameron C.G., McFarland S.A., Obaid G. Enabling *In vivo* optical imaging of an osmium photosensitizer by micellar formulation. *Pharmaceutics.* 2022. **14**(11): 2426.
52. Prabha S., Vijay A.K., Mathew D.E., George B. Light sensitive orange carotenoid proteins (OCPs) in cyanobacterial photoprotection: evolutionary insights, structural–functional dynamics and biotechnological prospects. *Arch. Microbiol*. 2025. **207**(2): 32.
53. Martella E., Dozza B., Ferroni C., Obeyok C.O., Guerrini A., Tedesco D., Manet I., Sotgiu G., Columbaro M., Ballestri M., Martini L., Fini M., Lucarelli E., Varchi G., Duchi S. Two Beats one: osteosarcoma therapy with light-activated and chemo-releasing keratin nanoformulation in a preclinical mouse model. *Pharmaceutics.* 2022. **14**(3): 677.
54. Al-Jamal A.N., Al-Hussainy A.F., Mohammed B.A., Abbas H.H., Kadhim I.M., Ward Z.H., Kar Mahapatra D., Joseph T.M., Kianfari E., Thomas S. Photodynamic Therapy (PDT) in drug delivery: Nano-innovations enhancing treatment outcomes. *Health Sciences Review.* 2025. **14**: 100218.
55. *Medical chemistry and clinical application of silicon dioxide.* Edited by A.A. Chuiko. (Kyiv: Naukova dumka, 2003). P. 416. [in Russian].
56. *Surface Physics and Chemistry*. Book II. Surface Chemistry. Edited by Kartel N.T. and Lobanov V.V. (Kyiv: Chuiko Institute of Surface Chemistry, 2018). V. 1. [in Russian].
57. *Surface Physics and Chemistry*. Book II. Surface Chemistry. Edited by Kartel N.T. and Lobanov V.V. (Kyiv: Chuiko Institute of Surface Chemistry, 2018). V. 2. [in Russian].
58. *Surface Physics and Chemistry*. Book II. Surface Chemistry. Edited by Kartel N.T. and Lobanov V.V. (Kyiv: Chuiko Institute of Surface Chemistry, 2018). V. 3. [in Russian].
59. Jo S.D., Ku S.H., Won Y.Y., Kim S.H., Kwon I.C. Targeted nanotheranostics for future personalized medicine: recent progress in cancer therapy. *Theranostics*. 2016. **6**(9): 1362.
60. Obaid G., Broekgaarden M., Bulin A.-L., Huang H.-C., Kuriakose J., Liu J., Hasan T. Photonanomedicine: a convergence of photodynamic therapy and nanotechnology. *Nanoscale*. 2016. **8**(25): 12471.
61. Fan W., Yung B., Huang P., Chen X. Nanotechnology for multimodal synergistic cancer therapy. *Chem. Rev*. 2017. **117**(22): 13566.
62. Dujardin C., Auffray E., Bourret-Courchesne E., Dorenbos P., Lecoq P., Nikl M., Vasil'ev A., Yoshikawa A., Zhu. R.-Y. Needs, trends, and advances in inorganic scintillators. *IEEE Transactions on Nuclear Science*. 2018. **65**(8): 1977.
63. Algorri J.F., Ochoa M., Roldán-Varona P., Rodríguez-Cobo L., López-Higuera J.M. Light technology for efficient and effective photodynamic therapy: a critical review. *Cancers*. 2021. **13**(14): 3484.
64. Yan J., Li B., Yang P., Lin J., Dai Y. Progress in light-responsive lanthanide nanoparticles toward deep tumor theranostics. *Adv. Funct. Mater.* 2021. **31**(42): 2104325.
65. Yang X., Gao L., Guo Q., Li Y., Ma Y., Yang J., Gong C., Yi C. Nanomaterials for radiotherapeutics-based multimodal synergistic cancer therapy. *Nano Res.* 2020. **13**(10): 2579.
66. Wang C., Cheng L., Liu Z. Drug delivery with upconversion nanoparticles for multi-functional targeted cancer cell imaging and therapy. *Biomaterials*. 2011. **32**(4):1110.

67. Yang D., Kang X., Ma P., Dai Y., Hou Z., Cheng Z., Lin J. Hollow structured upconversion luminescent $NaYF_4$:Yb^{3+}, Er^{3+} nanospheres for cell imaging and targeted anti-cancer drug delivery. *Biomaterials*. 2013. **34**(5): 1601.
68. Alves L.A., Ferreira L.B., Pacheco P.F., Mendivelso E.A.C., Teixeira P.C.N., Faria R.X. Pore forming channels as a drug delivery system for photodynamic therapy in cancer associated with nanoscintillators. *Oncotarget.* 2018. **9**(38): 25342.
69. Horbatok K., Makhnii T., Kosach V., Danko V., Kovalenko A., Fatiushchenkov S., Borysko P., Pishel I., Babii O., Ulrich A.S., Schober T., Afonin S., Komarov I.V. *In Vitro* and *In Vivo* Evaluation of Photocontrolled Biologically Active Compounds - Potential Drug Candidates for Cancer Photopharmacology. *J. Visualized Exp.* 2023. **29**(199): e64902.
70. Sarabando S.N., Palmeira A., Sousa M.E., Faustino M.A.F., Monteiro C.J.P. Photomodulation Approaches to Overcome Antimicrobial Resistance. *Pharmaceuticals*. 2023. **16**(5): 682.
71. Ma X., Johnson D.A., He X.J., Layden A.E., McClain S.P., Yung J.C., Rizzo A., Bonaventura J., Banghart M.R. *In vivo* photopharmacology with a caged mu opioid receptor agonist drives rapid changes in behavior. *Nat. Methods*. 2023. **20**(5): 682.
72. Jia S., Sletten E.M. Spatiotemporal Control of Biology: Synthetic Photochemistry Toolbox with Far-Red and Near-Infrared Light. *ACS Chem. Biol*. 2022. **17**: 3255.
73. Paoletti P., Ellis-Davies G.C.R., Mourot A. Optical control of neuronal ion channels and receptors. *Nat. Rev. Neurosci*. 2019. **20**(9): 514.
74. Tang Y., Hu J., Elmenoufy A.H., Yang X. Highly Efficient FRET System Capable of Deep Photodynamic Therapy Established on X-ray Excited Mesoporous LaF_3:Tb Scintillating Nanoparticles. *ACS Appl. Mater. Interfaces*. 2015. **7**(22): 12261.
75. Kusyak A., Petranovska A., Oranska O., Turanska S., Shuba Ya., Kravchuk D., Kravchuk L., Sotkis G., Nazarenko V., Kravchuk R., Dubok V., Bur'yanov O., Chornyi V., Sobolevs'kyy Yu., Gorbyk P. Chapter 3. *Synthesis and Properties of Nanodispersed Luminescent Structures Based on Lanthanum Fluoride and Phosphate for Optopharmacology and Photodynamic Therapy of Tumor Diseases Localized in Cranial Organs and Bone Tissues. What to Know about Lanthanum*. Catherine C. Bradley (Editor). (Nova Science Publishers, NY, USA, 2023).
76. Kusyak P., Shchehlov O.D., Oranska O.I., Kravchuk R.M., Gorbyk P.P. Nanodispersed X-Ray Phosphors LaF_3:Tb^{3+}, $LaPO_4$:Tb^{3+}, Hydroxyapatite:Tb^{3+}:Obtaining and Ray Luminescence Properties. *Theor. Exp. Chem.* 2025. **60**: 403.
77. Chien H.-W., Huang C.-H., Yang C.-H., Wang T.-L. Synthesis, Optical Properties, and Sensing Applications of LaF_3:Yb^{3+}/Er^{3+}/Ho^{3+}/Tm^{3+} Upconversion Nanoparticles. *Nanomaterials* 2020. **10**(12): 2477.
78. Jin X., Zhuang J., Zhang Z., Guo H., Tan J. Hydrothermal synthesis of hydroxyapatite nanorods in the presence of sodium citrate and its aqueous colloidal stability evaluation in neutral pH. *J. Colloid Interface Sci*. 2015. **443**: 125.
79. Wang C., Jeong K.-J., Kim J., Kang S.W., Kang J., Han I.H., Lee Il-W., Oh S.-J., Lee J. Emission-tunable probes using terbium(III)-doped self-activated luminescent hydroxyapatite for in vitro bioimaging. *J. Colloid Interface Sci*. 2021. **581**(A): 21.
80. Chen Y., Gu W., Pan H., Jiang Sh., Tang R. Stabilizing amorphous calcium phosphate phase by citrate adsorption. *CrystEngComm.* 2014. **16**(10): 1864.
81. Caldorera-Moore M., Guimard N., Shi L., Roy K. Designer nanoparticles: incorporating size, shape and triggered release into nanoscale drug carriers. *Expert Opin. Drug Deliv.* 2010. **7**(4): 479.
82. Danaei M., Dehghankhold M., Ataei S., Davarani F.H., Javanmard R., Dokhani A., Khorasani S., Mozafari M.R. Impact of Particle Size and Polydispersity Index on the Clinical Applications of Lipidic Nanocarrier Systems. *Pharmaceutics*. 2018. **10**(2): 57.
83. Yan B., Gu J., Xiao X. $LnPO_4$: RE^{3+} (La = La, Gd; RE = Eu, Tb) nanocrystals: solvo-thermal synthesis, microstructure and photoluminescence. *J. Nanopart Res.* 2010. **12**: 2145.
84. Labrador-Páez L., Kostiv U., Widengren J., Liu H. Water: An Influential Agent for Lanthanide-Doped Luminescent Nanoparticles in Nanomedicine. *Opt. Mater*. 2023. **11**: 2200513.
85. Devi N., Ray S.S. Electromagnetic interference cognizance and potential of advanced polymer composites toward electromagnetic interference shielding: A review. *Polym. Eng. Sci*. 2022. **62**(3): 591.
86. Narayanan S.N., Jetti R., Kesari K.K., Kumar R.S., Nayak S.B., Bhat P.G. Radiofrequency electromagnetic radiation-induced behavioural changes and their possible basis. *Environ. Sci. Pollut. Res.* 2019. **26**(30): 30693.
87. Wang H., Li S., Liu M., Li J., Zhou X. Review on Shielding Mechanism and Structural Design of Electromagnetic Interference Shielding Composites. *Macromol. Mater. Eng*. 2021. **306**(6): 2100032.
88. Kumar D., Moharana A., Kumar A. Current trends in spinel based modified polymer composite materials for electromagnetic shielding. *Mater. Today Chem*. 2020. **17**: 100346.

89. Almessiere M.A., Slimani Y., Trukhanov A.V., Sadaqat A., Korkmaz A.D., Algarou N.A., Aydın H., Baykal A., Toprak M.S. Review on functional bi-component nanocomposites based on hard/soft ferrites: Structural, magnetic, electrical and icrowave absorption properties. *Nano-Struct. Nano-Objects*. 2021. **26**(8): 100728.
90. Chang J., Zhai H., Hu Z., Li J. Ultra-thin metal composites for electromagnetic interference shielding. *Composites, Part B*. 2022. **246**: 110269.
91. Wei H., Yu Y., Jiang F., Xue J., Zhao F., Wang Q. Carbon@SiC(SiCnws)-$Sc_2Si_2O_7$ ceramics with multiple loss mediums for improving electromagnetic shielding performance. *J. Eur. Ceram. Soc.* 2022. **42**(5): 2274.
92. Bhingardive V., Woldu T., Biswas S., Kar G.P., Thomas S., Kalarikkal N., Bose S. Microwave Absorption in MWNTs-Based Soft Composites Containing Nanocrystalline Particles as Magnetic Core and Intrinsically Conducting Polymer as a Conductive Layer. *Chem. Select*. 2016. **1**(15): 4747.
93. Hosseini S.H., Moghimi A., Moloudi M. Magnetic, conductive, and microwave absorption properties of polythiophene nanofibers layered on $MnFe_2O_4/Fe_3O_4$ core–shell structures. *Mater. Sci. Semicond. Process.* 2014. **24**: 272.
94. Mazurenko R., Prokopenko S., Godzierz M., Hercog A., Makhno S., Szeluga U., Gorbyk P., Trzebicka B., Kartel M. Synthesis of nanosized spinel ferrites $MnFe_2O_4$ on the surface of carbon nanotubes for the creation of polymer composites with enhanced microwave absorption capacity. *Appl. Mater. Today.* 2023. **35**: 101972.
95. Mazurenko R., Prokopenko S., Godzierz M., Hercog A., Kobyliukh A., Gunja G., Makhno S., Szeluga U., Gorbyk P., Trzebicka B. Polymer Nanocomposites Based on Nanosized Substituted Ferrites $(NiZn)_{1-x}Mn_xFe_2O_4$ on the Surface of Carbon Nanotubes for Effective Interaction with High-Frequency EM Radiation. *Materials*. 2024. **17**(5): 986.
96. Kusyak A.P., Kusyak N.V., Oranska O.I., Kulyk T.V., Dzubenko L.S., Palianytsia B.B., Dudarko O.A., Korniichuk N.M., Petranovska A.L., Gorbyk P.P. Magnetosensitive Nanocomposite $Fe_3O_4/Al_2O_3/C$ Synthesis and Properties. *Nanosystems, Nanomaterials, Nanotechnologies*. 2023. **21**(2): 0427.
97. Makhno S., Wan X., Lisova O., Gorbyk P., Wang D., Tang H., Shi Y., Kartel M., Ivanenko K., Hozhdzinskyi S., Zaitseva G., Stetsenko M., Sementsov Y. Conducting Rubber Anisotropy of Electrophysical and Mechanical Properties. *Polymers*. 2025. **17**(4): 492.

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