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Nanotechnology in Medical Research: Applications and Prospects

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Abstract **Background:** The growing interest in innovative nanotechnologies and their application in medical practice encourages a systematic scientific understanding of their mechanisms of action, potential biological consequences and conditions for safe integration into research and experimental practices. The purpose of the research was to conduct an analytical generalization of approaches to the use of nanotechnology solutions in the medical field and create a conceptual model for their implementation in research systems. **Methods:** The research methodology was based on a systematic analysis of 56 scientific sources from 2022-2025. Within this framework, the directions of application of nanotechnology in medical research, properties of nanomaterials and biological responses were consistently studied. Safety approaches were also analysed, leading to the formation of a conceptual model. **Results:** The analysis revealed that the effectiveness of nanomaterials depends largely on their physicochemical characteristics, the ability to interact with biological structures and exposure conditions in specific research models. It was found that the biological response to nanomaterials is multilevel and contextual, highlighting certain barriers to predicting effects without taking into account safety factors, especially in studies related to neuropathology, where penetration through the blood-brain barrier and interaction with neuronal and glial cells pose specific risks. The generalization of the obtained provisions made it possible to highlight the risks associated with the occurrence of cellular cytotoxicity, disruption of membrane integrity, activation of inflammatory and immune reactions, as well as the cumulative accumulation of nanomaterials in tissues under conditions of repeated or prolonged interaction. **Conclusions:** The proposed conceptual model outlined the key stages of studies, where the combination of nanomaterial properties, exposure conditions and biological features of the system determines the effectiveness of a medical experiment and the level of biological risks. The results obtained can be used by scientists working in the field of biomedical research, including laboratory and preclinical models, as well as by developers of experimental protocols for the informed and safe implementation of nanotechnologies in laboratory and interdisciplinary research practice.

Key Words Biological Risk, Toxic Effects, Therapeutic Models, Intensive Care, Laboratory Studies, Neuropathology

INTRODUCTION

Nanotechnology in medical research is considered as a tool for expanding the degree of control over biological processes at the cellular and molecular levels, which facilitates targeted influence on pathological mechanisms within the framework of experimental and laboratory studies.

Traditional approaches often do not provide sufficient selectivity and predictability in interaction with biological structures, which limits their application. At the same time, the large-scale use of nanomaterials is associated with the potential unregulated risk of uncontrolled accumulation in organs and tissues, disruption of physiological processes and long-term adverse health effects. The lack of regulation in biosafety assessment procedures may cause further social and medical hazards, as well as hinder the rational and responsible use of nanotechnologies in the field of health care.

The application of nanotechnology methodologies in medical research aims to control biological processes at the cellular and molecular levels in diagnostic and therapeutic approaches. In the scientific work of Malik *et al.* [1], the directions of application of nanomaterials in medicine were outlined and it was demonstrated that nanoscale platforms increase the accuracy of molecular diagnostics and the selectivity of therapeutic action in controlled laboratory studies.

At the same time, the authors noted that the expansion of the scope of applications is accompanied by a greater complexity of interactions between nanoparticles and biological systems. Researchers Haleem *et al.* [2] analysed the medical areas of nanotechnology implementation and their effectiveness was determined by the factors of the size, surface properties and stability of nanostructures. The authors emphasized that the lack of regulation of these parameters affects the reproducibility of therapeutic effects and limits the possibility of their use in critical clinical scenarios, in particular, in intensive care. The report by Kazi *et al.* [3] demonstrated that the integration of nanomaterials into the "diagnostics-therapeutics" system has increased the functionality of medical research. Scientists also learned about another level of complications that manifest themselves during cascading biological interactions, indicating the importance of safety control and the prediction of the consequences of the use of nanotechnology.

The rapid development of nanotechnologies is accompanied by high risks of their uncontrolled accumulation in organs and tissues, the risk of disruption of biological functions, as well as long-term negative consequences. Insufficient regulation of biosafety assessment significantly affects the social and medical risk profiles and also complicates the safe application of nanotechnologies in the field of health care. The toxic effects of nanoparticles, documented in the study of Abbasi *et al.* [4], have demonstrated that size, morphology and surface charge, among structural parameters, play a crucial role. The authors found that the variability of these properties leads to unpredictable biological responses, as well as to complex issues in establishing safe limits for the use of nanomaterials. For example, the analysis of engineered nanomaterials for biomedical purposes has highlighted the presence of nanomaterials in various organs, which can disrupt physiological functions and change the functional status of biological systems, as evidenced by the academic paper of Umapathi *et al.* [5]. Laboratory studies related to neuropathology are of particular interest, since the interaction of nanomaterials with neuronal and glial cells, as well as the ability to cross the blood-brain barrier, pose specific risks of neurotoxicity. Studies by Ahmad *et al.* [6] showed that nanocarriers in drug delivery systems make it difficult to predict toxic effects and adverse reactions become more frequent and dangerous in models of acute neurological conditions relevant to intensive care. Based on the fact that nanotechnologies have acquired a systemic nature, it has become necessary to strengthen the safety control of their use and to clarify clear biological effects. The regulatory and ethical dimensions of nanotechnology in medical research are problematic due to inadequate risk control and social responsibility for the consequences of technological decisions. Current methods of regulating nanomedical products, as reviewed in Mangla *et al.* [7], have fragmented requirements for safety assessment and uneven control at different stages of their use. Such regulatory heterogeneity complicates the responsible use of nanotechnology and can lead to systemic risks for medical institutions, in particular, when introducing innovations in intensive care units. Ethical and legal analysis has shown that the use of nanotechnology in medicine raises the issue of informed consent, as reported by Wasti *et al.* [8]. Therefore, uncertainty about ethical boundaries can have negative consequences for the level of trust in medical innovations by society. Halamoda-Kenzaoui *et al.* [9] describe that the results of the development of regulatory science indicate a lack of coordination between scientific, clinical and supervisory structures, which prevents the existence of effective risk control measures. This means that the lack of coordinated regulatory strategies limits the safe implementation of nanotechnology in the healthcare system.

The available information on the mechanisms of nanotechnology in medicine does not sufficiently describe the integration of the use of nanomaterials in the field of health care, their biological risks and regulatory and ethical restrictions. The purpose of the research was to analyse scientific approaches to the application of nanotechnology in the field of medical research and, on this basis, to develop a conceptual model of their implementation. The following research tasks were established in order to accomplish the goal: analysing the primary areas of application of nanotechnology in medical research; summarizing the primary biological risks and safety limitations of nanomaterials in various research contexts; and creating a conceptual model for the efficient and secure application of nanotechnology in medical research.

This research was aimed at analysing the features of the use of nanotechnologies as part of the medical research system. The overall goal was to find common features that determine the scientific feasibility, methodological complexity and safety considerations of the use of nanotechnological solutions in the biomedical environment. To this end, the results of modern scientific approaches and research directions were summarized, which became the basis for further theoretical understanding of the problem.

In addition, the present academic paper is focused on a systematic analysis of the main factors that hinder the interpretation of the results of medical experiments on the introduction of nanomaterials, including the heterogeneity of their physicochemical properties, biological behavior and safety risks. Special attention is paid to the conditions under which nanomaterials interact with neuronal and glial structures, which creates specific limitations for neuropathological models. The idea was to identify the main shortcomings of current strategies and fit them into an integrated analytical framework. The final step to achieve the goal was to create a conceptual model that could structurally reflect how nanotechnology is integrated into the medical research system and serve as a basis for further scientific generalizations.

Nanotechnology in medicine is conceptualized as an arsenal for studying biological processes at the nanoscale of interactions and optimizing material properties for biomedical applications. The diversity of functional

properties (size, morphology, surface) found in nanomaterials has been described in numerous studies, which predict a variety of interactions with cell membranes, protein coronas and tissue microenvironments [9-11]. At the same time, it was noted that the increasing complexity of nanoplatforms creates a need for a new approach to experimental design, since small changes in physicochemical parameters can cause radically different biological effects [12,13]. At the conceptual level, nanomedicine is considered as a system with elementary capabilities and limited application, in which technological novelty does not eliminate the framework of biocompatibility and risk control [14].

At the international level, the picture of the implementation of nanotechnology in medical research is also uneven, but there is strong institutional support for interdisciplinary programs and the success of scientific systems in providing a full cycle - from materials science to biomedicine. Achieving faster integration of nanotechnology in countries that have developed research infrastructure has been one aspect of the interdisciplinary trend for biomedicine [15]. However, scientists Wu and Gu [16] have shown that in resource-poor conditions, fragmented paths prevail, characterized by unstable bases for transferring results into larger research programs. Studies on biomedical applications highlight the worldwide expansion of topics from natural biomedical frameworks to specialized areas, including neuropathology and neurodegenerative disorders, as well as orthopaedic technologies, which confirms the need for unified approaches to evaluating efficacy and safety [17-19]. This confirms the need for unified approaches to evaluating efficacy and safety, which are applied across different regulatory and scientific domains.

Functionalization and modification of the surface of nanoparticles have shown that the manipulation of the "nanomaterial-bioenvironment" significantly affects the availability of selectivity of the interaction, the stability of the system and the reproducibility of experimental results [18]. It has been found that the chemical effects of functionalization alter the bioactivity and binding kinetics of biological targets, forming multiple response profiles of cell bodies [11]. Scientists Xu *et al.* [20] found that for lipid nanoparticles, their modification affects the biodistribution and cellular uptake. Similarly, it has been proven that methods of transforming biomaterials in different areas constitute a broader context in different areas, which determines the wider application of nanotechnology [20].

In the pharmacological orientation, nanotechnology is presented as a building block in the formation of multilayer delivery systems for complex molecules and for modelling the behavior of bioactive substances in time and space [13]. The pharmacokinetics of nanoparticles contains a complex structure and depends on many factors: platform parameters, physiological barriers and ways in which the drug is excreted, which must be analysed and verified in detail [20]. Physicochemical aspects, toxicology and application of nanotechnology are described by Cai *et al.* [13] who showed that before starting the application of nanotechnology, the methodology must be agreed upon, the measurement must be consistent and the initial properties standardized to avoid ambiguity in the causal inference process. Regarding targeted delivery for several clinically oriented models, it was emphasized that the transformation from "carrier as container" to "carrier as active element of the system" fundamentally changes both the logic of setting up medical experiments and the conditions for determining effects, which is especially significant for models of acute conditions relevant to intensive care [21-23].

Regarding the highest intensity of nanotechnology development in medical research, most of them have been applied to oncology, where the tasks of detection, delivery, visualization and resistance (to the immune system) were performed simultaneously and in combination. Integrated approaches in nano-oncology constitute a multi-level experimental system, where the focus is on diagnostics and therapeutic effect, but there is a need for control over variables and the availability of transparent evaluation criteria [24]. Generalizations regarding nanotechnology in oncology focus on biosynthesis, agent delivery and theragnostic, highlighting the fact that as the functionality of the platform increases, so does the complexity of studying mechanisms of action and safety profiles [25]. It is emphasized that the approaches used to overcome resistance to nano-delivered drugs have been intrinsically aligned with molecular mechanisms (as opposed to general pharmacodynamics), so that potentially misleading conclusions can arise [26].

The threats that nanotechnology poses to medical research are also systemic, beyond the toxicity of individual materials. It has been found that complex nanomaterials (particularly carbon nanostructures) have unique biomolecular interaction features and require new models for hazard assessment and degradation regimes [27]. The focus of policy and moral scrutiny has been on the speed at which technological development is occurring, rather than on the harmonization of regulatory norms, which has made the criteria for acceptability and the limits of liability ambiguous [28]. This makes the issue of nanotechnology in medicine more perceptible as a combination of scientific-methodological and socio-legal constraints that define the limits of acceptability of research practices.

Most of the discrepancies in the conclusions of previous scientific works arise at the intersection of three dimensions: different initial factors of nanomaterials, different bio models and differentiated assessment of effects and risks. The lack of a standardized framework makes it difficult to create stable generalizations regarding biocompatibility, functionality of nano-delivery and the context of multi-component platforms. This justifies the urgent need for further studies and analysis of the systems approach and the formation of a conceptual model for medical research using nanotechnology.

However, despite the growing body of literature on nanotechnology in medicine, there is a lack of integrative frameworks that systematically combine nanomaterial properties, biological responses and safety considerations within a unified research model. This gap limits the reproducibility and methodological consistency of nanomedical studies. Therefore, the present study aims to address this limitation by developing a conceptual model for the implementation of nanotechnology in medical research.

The objectives of the study were:

- To analyse the main areas of application of nanotechnology in medical research;
- To summarize biological risks and safety limitations of nanomaterials;
- To develop a conceptual model for the implementation of nanotechnology in research systems

METHODS

The research was conducted as a theoretical analytical study, which includes components of a systematic review of scientific sources. International abstract and full-text databases were used to search for relevant publications (Scopus, Web of Science, PubMed). For the purpose of forming search queries, keywords and phrases in English were used, in particular, as follows: nanotechnology in medical research, nanomedicine, biomedical nanomaterials, nanoparticles in diagnostics and therapy, surface functionalization of nanoparticles, nanotechnology safety and toxicity, nanotechnology in oncology, laboratory-based nanomedicine studies, nanotechnology in neurodegenerative and neurological models, nanotechnology in critical care, AI and nanomedicine. The research included articles from peer-reviewed scientific journals or academic publications that were relevant to the topic of nanotechnology applications in medical research, had a clearly defined scientific approach or analytical conclusions and were available in full text. Exclusion criteria include: non-peer-reviewed articles; duplicate results; studies focused exclusively on technical aspects of nanomaterials that were not relevant to medical research. Sources were selected and initially assessed by two independent reviewers with a background in biomedical sciences and medical technology and twenty years of experience. 56 scientific publications from 2022-2025 were selected for analysis. The search strategy was designed to ensure reproducibility, including predefined keywords, database selection criteria and independent screening by two reviewers. Any disagreements were resolved through discussion.

The screening process included title and abstract evaluation followed by full-text assessment to ensure relevance and methodological quality.

The object of analysis focused on the potential applications of nanomaterials in biomedical experimental models [29,30], types of nanostructures and nanocarriers [31,32], characteristics of nanomaterials in clinical applications with biological systems [33], as well as methods for assessing safety and their biological risk profiles [34]. Particular attention was paid to approaches to implementing nanotechnology into research protocols [35], interdisciplinary collaboration [36] and the nature of methodological shortcomings [37] that have affected the academic interpretation of medical research results. The analysis method was used to characterize the main methods and factors of the issue of using nanotechnology in medical research. The synthesis provided the integration of heterogeneous scientific positions into a comprehensive picture of nanotechnology contributions and placement in modern biomedical science. In the global scientific discourse, the comparative method made it possible to contrast different scientific methodologies, applications of nanomaterials and their biological roles. Establishing structural concepts on the tendencies and constraints of nanotechnology applications in medical science was made possible by generalization. A conceptual framework for the application of nanotechnology in the medical research system was created by using abstraction to conceptually isolate important qualities from application and industry data. The conceptual model was developed through iterative synthesis of recurring patterns identified across the analysed studies.

Ethical approval was not required as the study did not involve human or animal subjects.

RESULTS

Main Areas of Application of Nanotechnology in Medical Research

The development of nanotechnology in medical research contributes to the formation of a new level of experimental analysis of biological systems, based on the possibility of controlled interaction with cellular and subcellular structures in laboratory research conditions. Unlike traditional approaches, nanomaterials are used not as an independent therapeutic technology, but as a tool for studying the mechanisms of pathological processes, biological response and functional organization of tissues. Nanotechnology is considered primarily as a research platform that allows expanding the boundaries of observation and modelling of biomedical phenomena [38].

It was discovered that experimental diagnostics has become the fundamental direction of nanotechnology application in the medical field. Nanoparticles, different in morphology and chemical nature of the composition, are used as markers to detect changes at the molecular and cellular levels, which allows analysing the early stages of pathological processes in controlled model systems of laboratory research [39]. In experiments, nanomaterials are used as signal amplifiers or platforms for selective binding to biomolecules, which significantly improves the accuracy of experiments. One of the advantages of this approach is the ability to study dynamic processes without disrupting the physiological integrity of the system [40]. Thus, there is a trend towards a therapeutic experimental approach, where the application of nanotechnology is used to study the mechanisms

Table 1: Analytical systematization of areas of application of nanotechnology in medical research

Direction of application	Methodological role in the research	Type of experimental task	Level of biological organization
Experimental diagnostics	Analysis sensitivity enhancement tool	Early detection of changes and monitoring of dynamics	Molecular, cellular
Therapeutic experimental models	Platform for studying mechanisms of action	Analysis of the effect dependence on localization and dose	Cellular, tissue
Targeted delivery (as a research tool)	Selective interaction model	Study of receptor and barrier mechanisms	Membrane, subcellular
Personalized experimental models	Response variability analysis tool	Modeling individual reaction scenarios	Cellular, systemic
Integrated nanotechnology platforms	System analysis tool	Processing of multivariate experimental data	Systemic
Safety studies on nanomaterials	Risk control component	Assessment of cumulative and side effects	Cellular, tissue
Laboratory models of neuropathology and critical conditions	Systemic and neurocellular response assessment platform	Modeling damage, barrier effects and acute reactions	Cellular, tissue, systemic

Source: compiled by the author during the analysis of scientific studies [29-34,38,39]

of action of bioactive compounds. The analysis showed that nanocarriers are used to control the mobility of molecules to different cellular targets, which makes it possible to study the dependence of concentration, time of exposure and localization of the effect. This contributes to a greater understanding of the biological pattern of interaction of nanomaterials with cellular systems than in a therapeutic system [31]. Such models are useful preclinical tools for evaluating new therapeutic strategies and their efficacy [30].

A few years ago, targeted delivery was considered as a means of experimental tool; now it is considered as a separate group of experiments. Nanostructures are used to study the mechanism of selective interaction of the system with receptors in the cell, the characteristics of the membrane barrier and intracellular transport. Nanotechnology has allowed the development of complex biological phenomena in which the surface properties, size and charge of particles are the main factors. This is an environment for studying the basic cellular biological processes that still remain unexplored [29]. Such models are of particular importance in laboratory studies of neuropathology, where the surface characteristics, size and charge of nanoparticles determine the ability to overcome the blood-brain barrier and interact with neuronal and glial cells [30].

Nanomaterials have allowed for fine-tuning of interaction parameters, which has enabled the modelling of different response scenarios to identical exposures. This has contributed to the creation of new research paradigms that have been developed to elucidate the mechanism of individual pathological changes [33].

Meanwhile, modern medical research has evolved and created a trend of new systems consisting of unified experimental platforms combining nanotechnology and digital, computational and analytical approaches in the field of medical experiments. These platforms facilitate the analysis of large volumes of experimental data obtained from multiparameter studies of the interaction of nanomaterials with biological systems [38]. The combination of nanomaterials with mathematical modelling and artificial intelligence algorithms has expanded the possibilities of predicting biological responses depending on the properties of nanomaterials and experimental conditions, which is relevant for models of acute conditions relevant for intensive care.

With the expansion of nanotechnology applications in medical research, biosafety issues have also come to the fore and have even become systemic in the field of preclinical experimental models. Nanomaterials have adverse biological effects that are a consequence of their chemical composition, size, shape, surface properties and bioaccumulation potential [40]. Some studies have shown that prolonged or repeated treatment with nanomaterials can alter cellular functions, induce inflammation and promote changes in physiological processes at the tissue level [34]. Predicting long-term effects was particularly difficult, since the impact on biological cells did not depend on how the parameters of nanomaterials and experimental conditions were combined. As a result, safety issues went beyond the process of assisting in basic approaches to medical research and became an integral part of the use of nanotechnologies. The generalization of the results of the analysis made it possible to systematize the key areas of application of nanotechnologies in medical research. The main areas of application are summarized in Table 1.

Analytical understanding of the results presented in Table 1 showed that the application of nanotechnology in the field of medical research has formed a multi-level research system, within which technological solutions perform an instrumental, rather than an applied function. As it turned out, nanomaterials and nanocarriers do not replace traditional experimental methods but expand their analytical capabilities, allowing the study of processes that previously remained beyond the scope of direct observation and also help to model possible scenarios of reactions to a particular action. The capacity of nanostructures to be included in intricate research designs that combine physicochemical properties with the system's biological response is particularly significant. Such integration facilitates the transition from fragmentary analysis of individual indicators and parameters to a systematic study of the mechanisms of functioning of biological objects under controlled conditions. Laboratory studies of neuropathology and acute models were also important, where the combination of precise parameter control and safety assessments is critical for the potential translation of results into intensive care practice. The revealed dependence of the results on a set of certain characteristics of nanomaterials emphasizes the need to consider them as an active factor of the experiment and not just a carrier. Thus, the results of the analysis confirmed

that the main directions of application of nanotechnologies in medical research form a single and complete methodological platform focused on in-depth analysis of biological processes, modelling of complex interactions and increasing the analytical accuracy of experiments. At the same time, the multifunctionality of nanotechnological solutions determines the increasing role of safety aspects, which cannot be considered separately from the effectiveness of research approaches.

Biological Risks and Safety Limits of Nanomaterials

The increasing use of nanotechnology for medical research raises new challenges for biosafety, arising from the unique interaction of nanomaterials with living systems. Unlike traditional materials, nanostructures function at a scale commensurate with key elements of cellular organization, which leads to a fundamentally different nature of the biological response. Nanomaterials in scientific research have been recognized not only as simple research tools, but are also considered as agents that can influence the trajectory of biological processes, which requires addressing their threat [35].

The results of the analysis showed that the physicochemical properties of nanomaterials have become critically important determinants of biological safety. The size, shape, surface charge and chemical composition of nanoparticles are significant for cellular response. Even minor changes in these parameters can lead to qualitatively different biological responses - from adaptive changes in cellular metabolism to disruption of membrane integrity or induction of apoptosis [31]. This dependence made it difficult to establish universal safety parameters and required that each nanomaterial be considered in the context of a specific experimental design [33]. Another risk was the dynamic transformation of nanomaterials in biological environments. Nanoparticles absorbed proteins of biological fluids and other molecules through adsorption to the appearance of the so-called biomolecular corona. The process changed the initial properties of the material, modified the mechanisms of recognition by cells and influenced the subsequent biodistribution [40]. Thus, the biological activity of a nanomaterial is determined not only by its synthetic properties, but also by the environment in which it is used, which makes it much more difficult to predict its effects and safety margins. Processes that lead to the uptake of nanomaterials by cells or sub cells have created a special class of risks.

Nanoparticles can enter cells using several endocytosis pathways and localize to the endosomal-lysosomal system or mitochondria. However, this intracellular accumulation is not necessarily accompanied by immediate cytotoxicity, but can lead to disturbances in energy metabolism, activation of stress signalling pathways and alterations in gene expression. Such effects are of particular pathophysiological significance in laboratory models of neuropathology, since neuronal and glial cells are characterized by high metabolic activity, limited compensatory reserves and increased sensitivity to mitochondrial dysfunction. Intracellular localization of nanomaterials in neurons and astrocytes can disrupt synaptic transmission, axonal transport and calcium homeostasis, which creates conditions for delayed functional changes without pronounced early morphological signs of damage [31].

An additional risk factor in neuropathological models is the ability of certain nanomaterials to cross the blood-brain barrier or to affect its permeability, which expands the spectrum of potential neurotoxic effects. Such interactions may contribute to a chronic neuroinflammatory response, microglial activation and altered intercellular communication in neural tissue, which is particularly critical when modelling neurodegenerative processes, ischemic brain injury or traumatic lesions of the central nervous system [37]. Latent effects were largely due to prolonged or repeated exposure and were therefore poorly identified in standard short-term studies [30]. This indicates the methodological limitations of traditional toxicological approaches and emphasizes the need to use prolonged laboratory models of neuropathology with assessment of functional, metabolic and neurophysiological parameters.

Safety is a crucial component regarding nanostructures and targeted delivery. Their surface functionalization to increase the selectivity of binding to cellular targets modifies cellular uptake and intracellular transport systems [32]. Accordingly, the ability to distinguish the biological activity of the active compound under study from the effect of the transport platform itself has become important. This also complicates the interpretation of results and requires simultaneous assessment of the safety of nanostructures as an independent experimental factor. Much attention has been paid to the immunological aspect, from the point of view of biological safety. Even in the absence of significant toxicity, nanomaterials could interact with innate immune cells, stimulate proinflammatory mediators or modify the behaviour of macrophages [37]. Such reactions are not always clinically significant within the framework of a single study but pose a risk of cumulative effects and influence the results of experiments aimed at immune or inflammatory processes. This aspect is significant when modelling acute conditions relevant to intensive care, where the immune response plays a decisive role.

Interindividual differences in responses to biological signals also complicate safety issues. In personalized experimental models, it was found that cellular systems of different genetic and phenotypic variants respond differently to the same nanostructures, even for very different cellular systems. The formulation of universal safe concentrations was not methodologically acceptable and the safety margin became a kind of dynamic parameter that depended on the conditions of biological systems and exposure situations [33]. There was a second dimension of safety risks related to systemic and remote effects of nanomaterials. Changes in oxidative stress, disruption of cellular homeostasis or altered tissue functional status were recorded even in the absence of specific toxic effects [41]. These effects were

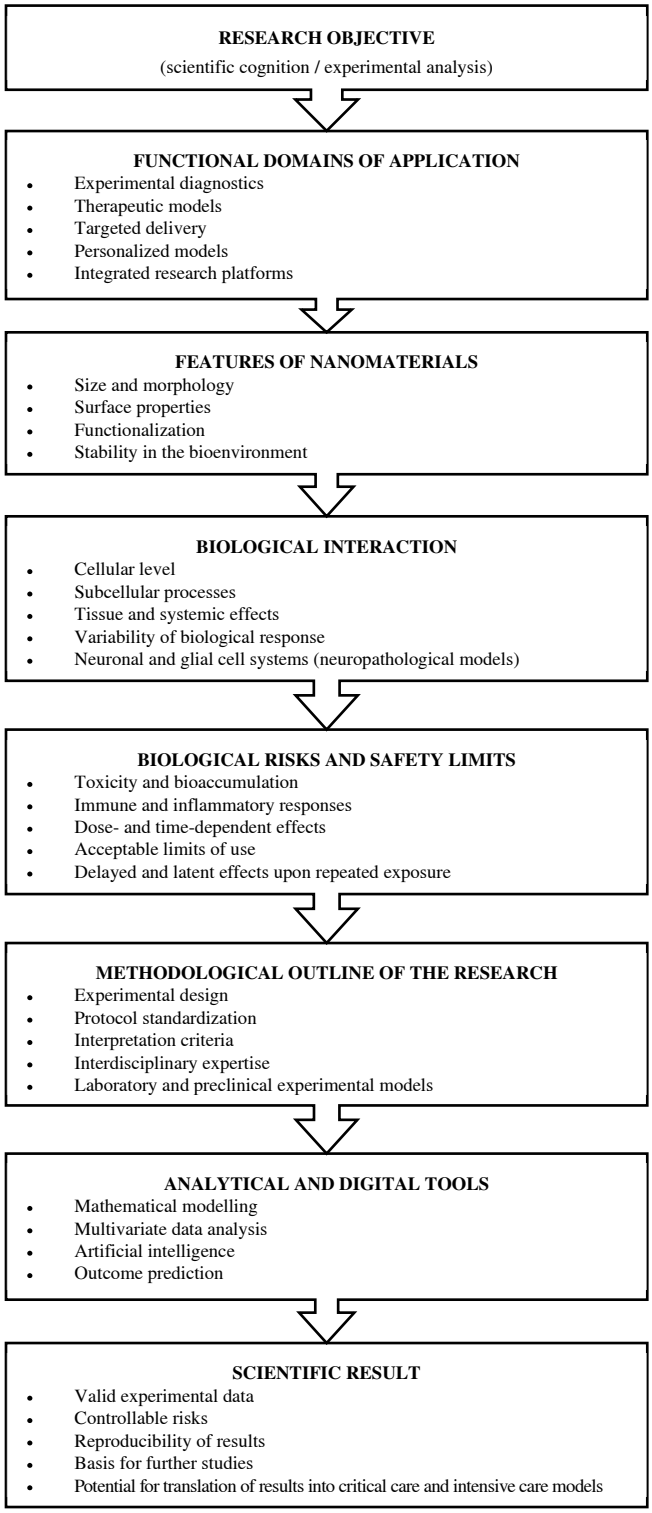

Figure 1: Conceptual model of the introduction of nanotechnology into medical research

Source: The author, during the analysis of scientific studies [29-33, 39-43]

known not to directly alter the outcome of a particular experiment, but could introduce biases into the system for repeated or combined use of nanomaterials used in any given trial or research routine. Comprehensive models were used that combined the analysis of efficacy, biodistribution and possible side effects, rather than a separate toxicological assessment. This approach decreased the possibility of incorrect interpretation and significance of the findings and better reflected the current state of interactions between nanomaterials and biological systems [34,39].

The biological risk posed by nanomaterials in medical research has a complex and context-dependent dimension, depending on specific factors. Based on the physicochemical characteristics of the nanostructures, the biological system and the experimental conditions, the use of unified safety criteria becomes impossible, since the limits of safe application are established. This situation requires the construction of a conceptual model through which risk assessment can be systematically integrated into the overall logic of medical research.

Conceptual Model of Nanotechnology Implementation in the Research

The revealed fragmentation and lack of a holistic view of the importance of nanomaterials in research activities led to the need to create a conceptual model for the implementation of nanotechnologies in medical research. As it turned out during the analysis, nanotechnologies were considered either through the prism of individual areas of application or in the context of specific safety aspects, which made it difficult to integrate the results obtained into a broader methodological context [35]. Therefore, there was a need for a generalizing conceptual framework that could combine the technological capabilities of nanomaterials, the patterns of biological response and the requirements for safe use within a single research space. The conceptual framework is illustrated in Figure 1.

The proposed conceptual model is based on the idea that nanotechnology is not considered as an isolated tool but as an integral part of medical research, interacting in a biological, methodological and analytical context. The central element of the scientific work is the research goal, since it determines the areas of application, parameters for nanomaterials and the logic of analysis. On this basis, the model is structured around interconnected blocks, the implementation of which is possible only within the framework of a pre-designed laboratory experimental design. The implementation of nanotechnology can be considered as a process that can be controlled and carried out in stages, rather than as separate experimental attempts [29,42]. The first structural block of the model describes the functional ways in which nanotechnology can be used in medicine. These can include experimental diagnostics, therapeutic modalities, custom-made delivery systems, personalized research platforms and combined analytical strategies. These areas are not considered separately in the model, since in reality they are often combined in real research practices. For example, the use of nanostructures in therapeutic models is inevitably associated with diagnostic monitoring and analysis of biological response, which confirms the feasibility of a systems approach to classifying areas of use [30,41].

Block 2 of the conceptual model deals with the properties of nanomaterials and their limitations in application and safety. The model emphasizes that no physicochemical characteristic of materials is a fixed property of nanostructures. Certain characteristics (shape, size, surface charge, chemical composition and degree of functionalization) depend on the biological environment and directly affect the type of interaction with cellular and tissue structures [31]. Accordingly, this block in the model is an "input filter" that assesses the suitability of a particular nanomaterial for a given research potential. The next structural dimension of the model concerns the biological response and is considered dynamic, multilevel and context-dependent. Under these circumstances, the model suggests that the impact of nanomaterials on biological systems should be built taking into account the cell type, tissue microenvironment and exposure conditions, as well as the specificity of neuronal and glial cells in the case of using neuropathological laboratory models. The biological response can be based on molecular, cellular and systemic levels and may not be linear or predictable [33]. The model is not universal for the actions of nanomaterials in this regard and emphasizes the need to contextualize the analysis of experimental results.

The safety block occupies a separate place in the conceptual model at each stage of the research process, but is an important component of its development. Instead, the proposed model is aimed at parallel analysis of effectiveness and risks, in contrast to the standard method, where safety research is carried out only after obtaining the main conclusion. Thus, potentially toxic, immunological, cumulative and delayed effects of nanomaterials will be taken into account at the experimental design stage. This preventive strategy reduces the likelihood of confounding and also increases the reliability of research results [39,43]. The architecture of the model in this framework is informed by experiments and logical analysis and interpretative as well as analytical procedures as a logical system.

Standardization of describing the conditions of influence of nanomaterials and parameters of biological response is also taken into account in the model. At the same time, the shortcomings of strict standardization in conditions of high variability of biological systems become obvious, which requires adaptive methodological solutions. The compromise between integration and universality is considered as one of the main factors contributing to the introduction of nanotechnologies into medical research [40]. An important addition to the model is the analytical and digital toolkit for mathematical modelling, analysis of large data sets and artificial intelligence. These tools perform a supporting but strategically important function of interpreting the complex interactions between nanomaterials and biological systems, as well as optimizing experimental parameters [38]. The model also takes into account the interdisciplinary nature of modern medical research. Nanotechnology can be implemented to collaborate with specialized personnel in the fields of materials science, biology, medicine and analytics. At the conceptual level, this exchange is not seen simply as an additional aspect of the process but as an important element for the development of reproducible and scientifically sound results. This is especially important in the case of complex experimental systems, since the interpretation of data requires a holistic conceptual vision.

Analytical generalization confirms that the proposed conceptual model is not only a descriptive approach to individual applications of nanotechnology; it also constitutes a holistic methodological framework for systematic applications in medical research. By integrating application areas, nanomaterial properties, biological response, safety limitations and methodological approaches into a single logical framework, the approach improves the stability of decisions made in the research process. Thus, the conceptual model acts as a mechanism through which methodological integration transforms studies from unstructured applications of nanotechnology to a controlled and validated research procedure. Its implication establishes criteria for promoting reproducibility of results, reducing biological risks and building a comprehensive understanding of the role of nanotechnology in modern medical research, thus aligning with the goals and objectives of the research.

DISCUSSION

The results of the theoretical analysis confirmed that the application of nanotechnology in medical research cannot be easily described by a linear approach or a narrowly focused approach. Nanomedical solutions are formed as an interaction of technological, biological, methodological and analytical components within laboratory and preclinical models and their effectiveness and safety depend on the coordination of these levels. Such multi-level logic makes it possible to reconcile the different results presented in the scientific literature and explains the differences between studies, the results of which on the surface seem mixed. It is important to remember when interpreting the results that we have obtained that in the context of the research; the main feature of nanotechnologies is not necessarily the so-called "innovation": it is their ability to change the conditions of interaction with biological systems. This is in line with theories that contend that the biological response is mostly regulated by the functionalisation of nanomaterials' surfaces [44]. Simultaneously, this study highlights that such controllability is constrained by the intricacy of biological systems and cannot be accurately predicted from the physicochemical characteristics of nanomaterials.

Comparing the results with previous efforts to combine therapeutic strategies has helped to better understand the nature of the current differences. In the few reported applications of nanoparticles with natural or synthetic bioactive compounds, the most frequent focus has been on higher efficacy and selectivity of their action [44,45]. The conceptual model formulated in this research does not deny such conclusions but can be considered contextual, dependent on the context and experimental conditions. Thus,

the optimistic conclusions provided by the applied studies do not contradict the more cautious stance of this work but rather reflect different degrees of generalizability.

It is worth noting that the potential of personalized nanomedicine is a topic of active discussion, from material selection to prediction of biological response using algorithmic methods [46]. The results obtained in this analysis confirm that this direction is important and explain that personalization does not eliminate the inherent uncertainty of biological systems. In the proposed model, personalized methods are considered as a means of reducing variability but not eliminating it completely. Similar logic is applied to the implementation of artificial intelligence in combination with digital analytical tools. Several studies have emphasized the ability of machine learning algorithms to optimize selected nanomaterials and predict experimental information by optimizing the selection of nanomaterials [47,48]. These methods are considered auxiliary, based on the quality of the input data and are not sufficient to replace experimental validation. This is the reason why quantitative predictions of algorithms are not always possible in real laboratory biological models.

The interdisciplinary nature of nanotechnology research was also taken into account. Existing studies have suggested that nanobiotechnology is an alternative strategy to support the progress of science and medicine [49,50]. The analysis conducted in this research considers interdisciplinarity not only as a theoretical advantage but as a necessity for meaningful interpretation of its results. The divergence of opinions between scientific methods often led to inconsistencies in the literature and was integrated into the development of a conceptual model. Studies have identified various toxicological and immunological hazards associated with nanomaterials, especially after prolonged exposure [49,51]. The results of this research confirmed these warnings and were relevant in that the risk depends mainly on the research method. The new concept views safety as transversal with risks, not as a side effect of the research program, but as a fundamental feature.

Comparative analyses of clinical and surgical applications of nanotechnology also reveal another key feature. In applied studies, the technical advantages of nanomaterials are mostly considered in isolation from the methodological context [52,53]. This research demonstrates that such advantages are marginal compared to a properly constructed experimental design. This also explains the different results that identical nanomaterials show under different study conditions. The examination of the studies on the integration of nanotechnology with digital and bioengineering approaches, which are combined with nanotechnology in their interpretation of the results, is significant. In the scientific work of Uddin *et al.* [54], the integration of nanomaterials and algorithms of artificial intelligence, machine learning and 3D bioprinting technologies was investigated to improve flexibility and personalized treatment strategies in complex patient-centred clinical environments. In light of the presented conceptual model, approaches from these two perspectives are valid for considering nanotechnology as components of a multi-level system, where the use of digital analytics does not replace experimental data with changes in the processing methods in which the data are processed. At the same time, the results of Dey *et al.* [55] showed that biological variability is still a major limitation in high-precision targeted delivery systems and the universality of personalized solutions is lower. In this light, the generalizations achieved in the research explain why the integration of nanomedicine with algorithmic approaches is not sufficient to ensure stable reproducibility of results due to the lack of methodological control. Therefore, the considered studies do not contradict the concept of this research but actually complement it and prove conclusively that technological convergence is achieved through the systematic organization of experimental, biological and analytical studies [56].

The results of the data obtained also present an opportunity for a new interpretation of the problem of reproducibility. Recent studies report difficulties in reproducing nanomedical experiments, which are often due to the variability of biological systems. This explanation is complemented in this theoretical model by references to methodological fragmentation and insufficient coordination at different stages of the research. Reproducibility is therefore viewed as a systemic problem rather than just a technical one. On a practical level, the results of the study can be used to better plan medical research with nanotechnology. The proposed model can be used as a framework for defining research protocols, selecting nanomaterials and preliminary risk assessment, including laboratory models of neuropathology and the potential translation of findings into the context of critical conditions and intensive care. As a result, the research not only satisfied what the researchers aimed to do but also became a basis for future studies to strengthen the reproducibility, safety and consistency of nanotechnology methodology in medical research. The findings of this study support the proposed conceptual model by demonstrating the necessity of integrating nanomaterial properties, biological response and safety assessment within a unified methodological framework.

CONCLUSIONS

The conducted study made it possible to comprehensively understand the role of nanotechnologies in the structure of integration into medical research and achieve the set goal by moving from a fragmentary description of individual applications to a systematic analysis of their functioning within a single research activity. The results obtained confirmed the assumption that the effectiveness and scientific significance of nanotechnologies are determined not only by the properties of nanomaterials but primarily by the consistency of application areas, biological response characteristics and safety requirements, which was reflected in the developed conceptual model. The scientific novelty of the research lies in the formation of an integrative model that

allows interpreting the results of medical research using nanotechnology in a logically connected technological, biological and methodological context, which was not sufficiently presented in previous generalizations.

The results showed that the tasks were implemented, expanded by identifying systemic connections between solutions in experiments and the variation of biological effects, which indicates that the concept of the proposed approach is fully implemented. From the point of view of application, the results are based on the ability of the model to be used as a tool in planning medical and laboratory studies, organizing protocols and improving the consistency of data interpretation in nanomedical research. However, the research found several possible issues and noted that direct applications in clinical settings will be limited because the generalization process will be heavily dependent on the completeness and quality of the sources. Further scientific studies are recommended to focus on experiments that will test the proposed model in different biological systems, establish specific safety limits for certain types of nanomaterials and identify the possibilities of creating analytical methods with nanotechnology that integrate them with digital data processing methods. This sets the long-term prerequisites for building a more reproducible and methodologically consistent plan for the implementation of nanotechnology for use in medical development, contributing to further scientific progress in nanomedicine. The proposed model can be applied in the design of laboratory and preclinical studies to improve reproducibility and risk assessment.

Key Findings

- The effectiveness and safety of nanomaterials are strongly dependent on their physicochemical properties (size, surface charge, functionalization) and the biological context in which they are applied
- Biological responses to nanomaterials are multilevel, dynamic, and context-dependent, making outcomes difficult to predict without integrated safety assessment
- Neuropathological and critical-care-related models present heightened risks due to blood–brain barrier penetration, neuroinflammation, and cumulative intracellular effects
- A conceptual model integrating application domains, material properties, biological response, safety limits, and analytical tools improves reproducibility and interpretability of experimental outcomes

What is Known and What is New?

- Nanotechnologies enhance experimental diagnostics, targeted delivery, and mechanistic studies at cellular and molecular levels
- Nanomaterial–biological interactions are influenced by surface chemistry, morphology, and environmental conditions
- Biosafety concerns such as cytotoxicity, immune activation, and bioaccumulation have been widely reported
- Proposes an integrative conceptual model that embeds safety assessment into every stage of nanotechnology-based medical research
- Highlights the systemic and latent risks of nanomaterials, particularly in neuropathological and intensive care research models

What is the Implication, and What Should Change Now?

- Medical research protocols should adopt parallel evaluation of efficacy and biological risk, rather than sequential safety testing
- Interdisciplinary collaboration and the use of digital and AI-based analytical tools should become standard practice for interpreting complex nanobiological interactions

Limitations

This study is based on secondary literature analysis and lacks experimental validation of the proposed conceptual model. Additionally, the analysis was limited to publications from 2022-2025, which may restrict the generalizability of findings.

Ethical Statement

The Ethics Committee of the Private Higher Education Institution "Kyiv International University" has reviewed and approved this article (Approval No.34, 02.01.2026).

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