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Future Trends in Nanotechnology Safety: A Review Study

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ABSTRACTS: Nanotechnology has emerged as one of the most influential scientific and technological advances of the twenty-first century, offering transformative applications in medicine, agriculture, food production, environmental protection, and industrial manufacturing. Despite its remarkable benefits, the increasing use of engineered nanomaterials has raised important concerns regarding their potential effects on human health and the environment. Consequently, nanosafety has become an essential component of responsible nanotechnology development. Traditional toxicity assessment methods remain valuable; however, they are gradually being complemented by innovative approaches that emphasize prevention, prediction, and sustainability. Strategies such as Safe by Design, artificial intelligence-assisted toxicity assessment, computational risk prediction, continuous nano surveillance, green nanotechnology, and the One Health framework represent significant advances toward comprehensive safety evaluation. These approaches enable researchers to identify potential hazards during the early stages of material development, reduce dependence on extensive experimental testing, improve regulatory decision-making, and promote environmentally sustainable innovation. Furthermore, interdisciplinary collaboration among material scientists, toxicologists, environmental researchers, engineers, healthcare professionals, and policymakers is essential for developing internationally harmonized standards that ensure the safe commercialization of nanotechnology-based products. Future research should prioritize the integration of artificial intelligence, omics technologies, predictive computational models, real-time environmental monitoring, and life-cycle assessment to establish more accurate and efficient risk assessment systems. At the same time, regulatory agencies must continue updating safety guidelines to accommodate the rapid evolution of nanotechnology and its expanding applications. Ultimately, achieving a balance between technological innovation and safety will determine the long-term success and public acceptance of nanotechnology. By adopting proactive, evidence-based, and sustainable safety strategies, nanotechnology can continue to deliver substantial societal, environmental, and economic benefits while minimizing potential risks to present and future generations.

KEYWORDS: Nanotechnology safety, safe by design, toxicity assessment, risk prediction, environmental monitoring, green nanotechnology.

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INTRODUCTION

Nanomaterials possess unique physical and chemical properties, including high surface area, high reactivity, and distinctive surface characteristics, enabling superior performance compared to conventional materials. Nanotechnology has become one of the fastest-growing scientific fields this century, with widespread applications in medicine, agriculture, food production, environmental remediation, and industrial manufacturing (Ajdari *et al*., 2018; Hanan *et al*., 2025). These advantages have accelerated the commercialization of nanotechnology-based products and expanded their use across numerous sectors, creating significant opportunities for technological innovation and sustainable development (UNEP, 2023).

Despite these remarkable benefits, the increased production and widespread application of engineered nanomaterials have raised concerns about their potential impacts on human health and the environment. Their small size, high mobility, and complex interactions with biological systems can lead to toxic effects that are not always predictable using traditional chemical risk assessment methods (Savolainen *et al*., 2013; Wiesner *et al*., 2006). This has led to ensuring the safe development, manufacturing, use, and disposal of nanomaterials becoming an international scientific and regulatory priority (OECD, 2022).

Recent advances in nanosafety have shifted the focus from traditional hazard identification to predictive, preventive, and sustainable risk management strategies. Modern approaches integrate materials engineering, computational toxicology, artificial intelligence,

environmental monitoring, and systems biology to improve the accuracy and efficiency of nanomaterial safety assessments (Fadeel *et al*., 2018). In particular, the integration of machine learning and artificial intelligence has enhanced the prediction of nanomaterial toxicity through the analysis of large and complex environmental datasets, thereby reducing experimental costs and accelerating safety assessments (Lynch *et al.,* 2020).
Currently, safe design, green nanotechnology, nano hazard prediction, nano monitoring, and the One Health approach have emerged as complementary frameworks for promoting responsible innovation throughout the nanomaterial lifecycle. These strategies emphasize early risk prevention, environmentally sustainable material design, continuous exposure monitoring, and integrated protection of human, animal, and ecosystem health (OECD, 2023; Sørensen *et al*., 2021; WHO, 2021). Taken together, these developments represent the future direction of nanotechnology safety by supporting evidence-based regulatory decision-making while ensuring technological advancements are achieved without compromising environmental sustainability or public health.

Safe by Design

The concept of "safety by design" (SbD) has emerged as one of the most promising strategies for enhancing nanotechnology safety. This proactive approach aims to identify and mitigate potential hazards during material design while preserving the desired functional properties of nanomaterials, thereby reducing the likelihood of adverse effects on human health and the environment. This can be achieved by integrating safety considerations into the early stages of nanomaterial development, rather than relying solely on post-production risk assessment (OECD, 2023; Rasmussen *et al.,* 2019).

Modifying these properties can significantly impact the interaction of nanoparticles with biological systems, affecting their cellular uptake, biodistribution, survival, and toxicity. For example, biodegradable nanomaterials are increasingly being developed to maintain their intended therapeutic or agricultural functions while minimizing their long-term environmental accumulation and ecological impacts.

The framework focuses on improving the fundamental physical and chemical properties of nanomaterials, including particle size, shape, surface chemistry, crystallinity, solubility, surface charge, and biodegradability (Ajdari *et al*., 2018; Fadel *et al*., 2018) .

The success of the "safety by design" concept fosters close collaboration among materials scientists, toxicologists, engineers, industrial manufacturers, and regulatory bodies throughout the nanomaterial's lifecycle. This integrated strategy facilitates more efficient product development, reduces the costs associated with redesigning potentially hazardous materials, accelerates regulatory approvals, and enhances public confidence in nanotechnology-based products. Therefore, the design process concurrently considers risk identification, exposure assessment, environmental impact assessment, product performance, and regulatory requirements, rather than waiting until the market stage (OECD, 2022; Rasmussen *et al*., 2019).

The "safety by design" approach increasingly relies on computational modeling, predictive toxicology, artificial intelligence, and high-throughput screening techniques. These advanced tools enable researchers to predict the safety profiles of newly designed nanomaterials before large-scale production, thereby supporting sustainable innovation and promoting the development of nanotechnology products that combine high performance with enhanced safety for both humans and the environment (Lynch *et al*., 2020; Fadeel *et al*., 2018).

AI in Nano Safety

Artificial intelligence (AI) has emerged as a revolutionary technology for enhancing the safety of nanomaterials by improving the efficiency, accuracy, and predictive power of their risk assessment. Traditional toxicity assessments rely on extensive laboratory experiments, animal testing, sophisticated analytical equipment, and significant financial and time investments. In contrast, AI-powered approaches can rapidly process large and complex datasets, identify hidden patterns, and establish predictive relationships that are difficult to detect using traditional statistical methods. This accelerates nanomaterial safety research and reduces experimental costs (Lynch *et al*., 2020; Fadel *et al*., 2018).

Advanced deep learning models enhance predictive performance by identifying complex nonlinear interactions between multiple variables. Machine learning algorithms can integrate diverse physical, chemical, and biological data, including nanoparticle composition, size distribution, shape, surface charge, chemical functions, dissolution kinetics, and biological responses, to accurately predict the toxicity of nanomaterials. This allows researchers to assess potential risks before conducting large-scale in vivo or in vitro testing (Lynch *et al*., 2020; Neale *et al*., 2013).

This approach enables researchers to prioritize the safest and most effective nanoparticle formulations for experimental validation. Another important application of artificial intelligence in nanomaterial safety is high-throughput computational screening, where thousands of newly designed nanomaterials can be evaluated simultaneously based on their predicted biological and environmental behavior. This reduces laboratory workload, minimizes the use of laboratory animals, and accelerates the development of safer nanomaterials (Neil *et al*., 2013; Fadeel *et al*., 2018).

Artificial intelligence (AI) also plays an increasingly important role in automated image analysis and characterization of nanomaterials. AI-powered interpretation of electron microscopy (EMS) images and other imaging techniques can rapidly determine nanoparticle morphology, aggregation state, size distribution, and cellular uptake with greater accuracy and reliability than manual analysis. These capabilities improve the reliability of nanosafety studies and support standardized characterization protocols across different laboratories (Fadeel *et al*., 2018).

These intelligent systems will facilitate real-time toxicity prediction, adaptive risk assessment, and evidence-based decision-making. In the future, AI will be fully integrated with laboratory automation systems, digital twins, robotic experiments, and autonomous research platforms capable of continuous learning from newly generated experimental data. This ultimately supports the development of safer, more sustainable and efficient nanotechnology for industrial, environmental, agricultural and biomedical applications (Lynch *et al*., 2020; OECD, 2023).

Nano Risk Prediction

The modern field of nanosafety requires a shift in focus from retrospective risk assessment to predicting potential adverse effects before significant human or environmental exposure occurs. Traditional toxicity assessments, which relied primarily on experimentally observed biological responses, have been replaced by nano-risk prediction, which integrates computational methods with experimental evidence to estimate the safety profile of manufactured nanomaterials during the early stages of product development. This predictive capability supports evidence-based decision-making throughout the design, marketing, and regulatory approval phases of nanomaterials, while reducing uncertainty in safety assessment (Neil *et al*., 2013; OECD, 2022).

Advanced computational models combine toxicity data with physicochemical properties, such as particle size, shape, surface chemistry, solubility, and surface charge, as well as exposure and environmental transport characteristics. Quantitative structure-activity relationship (QSAR) models and physiologically based pharmacokinetic simulations (PBPKs) are used to predict the uptake, distribution, metabolism, excretion, and biological interactions of nanoparticles within living organisms. These computational tools provide valuable insights into potential risks while reducing reliance on intensive laboratory and animal testing (Lynch *et al*., 2020; Al-Shibli and Juda, 2026).

Prior to the emergence of clinical toxicity, recent advances in genomic technologies, including genomics, transcription, proteomics, and metabolism, have enhanced predictive risk assessment by revealing early molecular responses to nanomaterial exposure. The integration of multi-component datasets with artificial intelligence and machine learning algorithms has significantly improved the accuracy of toxicity prediction, enabling researchers to identify biomarkers associated with adverse biological effects and individual susceptibility (Fadeel *et al*., 2018; Lynch *et al*., 2020).

Future nanomaterial risk prediction systems are expected to integrate life-cycle assessment, environmental modeling, population exposure data, and real-world monitoring information into comprehensive predictive frameworks. These multidisciplinary approaches will enable regulators, researchers and manufacturers to anticipate potential risks more effectively, improve the design of nanomaterials and support their safer commercialization by making science-based regulatory decisions (OECD, 2022; OECD, 2023).

Nano Surveillance

"Nanomonitoring" refers to the continuous and systematic monitoring of manufactured nanomaterials throughout their lifecycle, including production, transportation, storage, consumer use, recycling, and final disposal. As a result, long-term monitoring is essential for understanding exposure pathways and assessing potential risks to human health and ecosystems. Continuous monitoring has gained increasing importance due to the potential for nanomaterials to undergo physical and chemical transformations during environmental exposure, affecting their mobility, stability, bioavailability, and toxicity (Savolainen *et al*., 2013; OECD, 2022).

It also allows for the assessment of their long-term environmental accumulation. This information provides a crucial scientific basis for environmental risk assessment and regulatory decision-making. Environmental nanomonitoring utilizes advanced analytical techniques capable of detecting and quantifying nanoparticles in air, water, soil, sediments, food products, and biological tissues. These monitoring systems facilitate the identification of environmental pollution and the assessment of nanoparticle transport and transformation (Wiesner *et al*., 2006; Alsultan *et al*., 2026). Personal exposure assessment, engineering controls, and medical monitoring programs contribute significantly to reducing occupational risks and improving industrial safety standards. Occupational monitoring is a key component of nanosafety, as workers involved in the manufacturing, packaging, transportation, and waste management of nanomaterials may be exposed to higher levels than the general population. Regular workplace monitoring contributes to this (OECD, 2022).

These intelligent monitoring systems will facilitate the rapid implementation of exposure control measures whenever nanoparticle concentrations exceed established safety thresholds, thus strengthening preventative risk management strategies. Emerging technologies, including wearable sensors, biosensors, devices, wireless environmental monitoring systems, and automated data analytics, are poised to revolutionize nano-monitoring by enabling real-time detection of nanoparticle concentrations in various occupational and environmental settings (OECD, 2023; Fadel *et al.,* 2018).

Green Nanotechnology

Green nanotechnology represents a multidisciplinary field that integrates nanoscience with the principles of sustainable development, green chemistry, and environmental protection. This approach supports the development of nanotechnology while minimizing its environmental impact and enhancing its long-term sustainability. Its primary goal is to develop environmentally friendly nanomaterials and manufacturing processes that reduce the consumption of hazardous chemicals, lower energy requirements, minimize waste generation, and conserve natural resources throughout the product lifecycle (UNEP, 2023; OECD, 2023).

Greenly synthesized nanoparticles often exhibit improved biocompatibility, lower toxicity, and reduced environmental impacts, while maintaining desirable physical, chemical, and functional properties. A key development in green nanotechnology is the biosynthesis of nanoparticles using plants, bacteria, fungi, algae, and agricultural waste. These biological systems provide natural reducing and stabilizing agents that replace the toxic chemical reagents commonly used in conventional nanoparticle synthesis (Ajdari *et al.,* 2018).

Green nanoparticles exhibit improved biocompatibility, reduced toxicity, and lower environmental impacts, while maintaining desirable physical, chemical, and functional properties (Ajdari *et al*., 2018). These innovations contribute to safer applications in medicine, agriculture, and environmental remediation. Another important goal of green nanotechnology is the development of biodegradable nanomaterials, which break down naturally after fulfilling their function. Biodegradable nanoparticles reduce their long-term persistence in the environment, minimize their bioaccumulation in food chains, and mitigate the environmental risks associated with long-lasting conventional nanomaterials (Fadil *et al*., 2018; OECD, 2023).

Green nanotechnology also supports the transition to a circular economy through recyclable nanomaterials, resource-efficient manufacturing, waste utilization, and environmentally sustainable production systems. Future research is expected to increasingly integrate renewable energy technologies, environmentally friendly solvents, life cycle assessment methodologies, and carbon footprint reduction strategies to achieve safer and more sustainable nanotechnology production (UNEP, 2023; Al-Hasnawi *et al*., 2025).

One Health Approach

The One Health framework has emerged as a comprehensive approach that recognizes the close interrelationship between human, animal, plant, and environmental health. Assessing the safety of nanomaterials requires considering interconnected environmental and biological processes, rather than focusing solely on their toxicity to humans. This holistic perspective has gained increasing importance in the field of nanomaterial safety, given the transport of these manufactured materials through various environments and biological systems throughout their lifecycle (WHO, 2021; Sørensen *et al*., 2021).

Integrated assessments are essential for understanding the cumulative impacts across multiple biological and environmental systems. For example, nanoparticles used in agricultural applications may accumulate in the soil, be absorbed by crops, enter livestock through feed, contaminate aquatic ecosystems through runoff, and ultimately reach humans via the food chain. These interconnected exposure pathways demonstrate that separate toxicity assessments are insufficient to adequately identify the overall risks associated with manufactured nanomaterials (Saba *et al*., 2025) .

One Health encourages multidisciplinary collaboration among clinicians. Veterinarians, toxicologists, ecologists, microbiologists, agricultural researchers, and regulatory bodies are all involved. Therefore, comprehensive nanotechnology safety assessments consider environmental exposure, biodiversity conservation, food safety, antimicrobial resistance, ecosystem services, and public health simultaneously. This collaborative approach facilitates more effective risk management and supports evidence-based regulatory policies that protect both human health and the environment (WHO, 2021; Hussain and Joudah, 2023).

Future nanotechnology safety research will increasingly integrate ecosystem-level monitoring, microbiome analysis, climate-related environmental changes, global monitoring networks, and advanced data-sharing platforms within the One Health framework. These multidisciplinary strategies will enhance international regulatory collaboration, improve predictive risk assessment, and ensure that nanotechnology continues to support sustainable development while minimizing risks to current and future generations (Sørensen *et al*., 2021; Joudah, 2023).

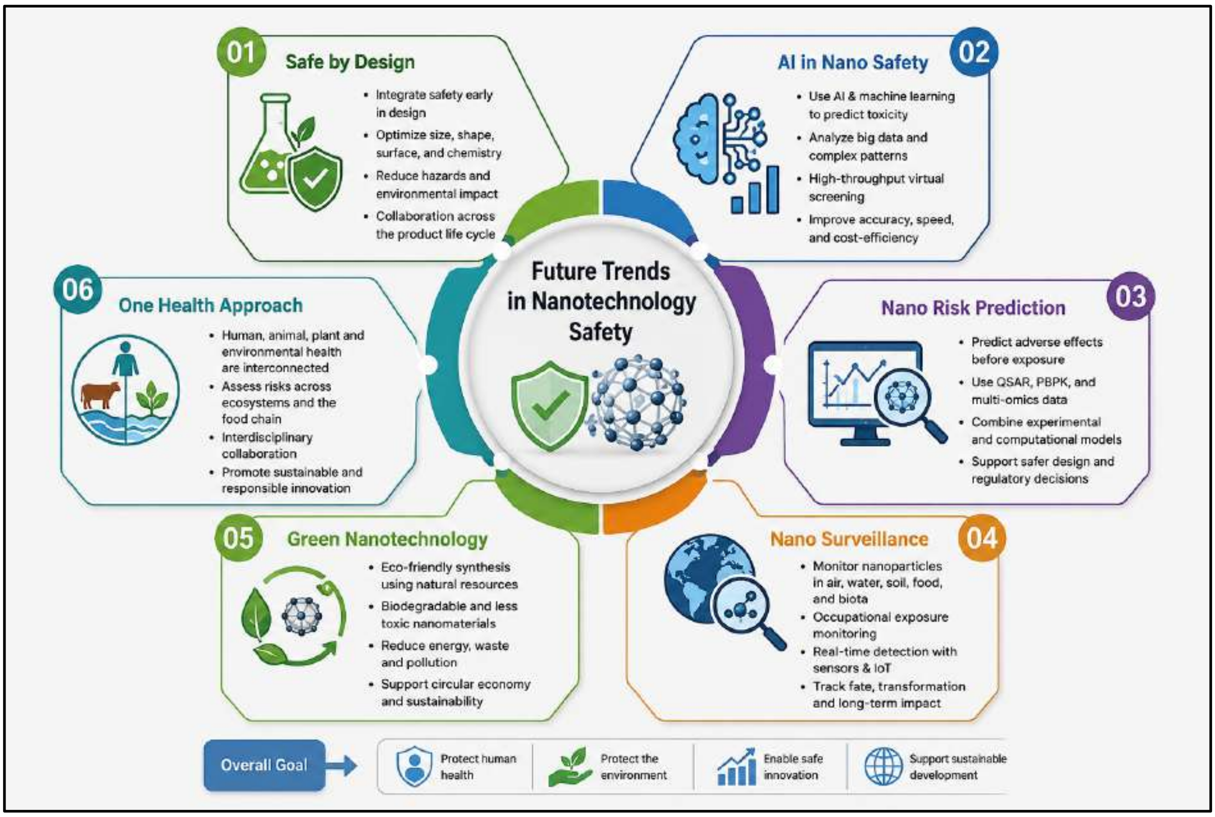

Figure 1. Conceptual Framework of Future Trends in Nanotechnology Safety

CONCLUSION

The future of nanotechnology safety is moving toward predictive, intelligent, and sustainable risk management strategies. Innovations such as Safe by Design, artificial intelligence, predictive toxicology, continuous nano surveillance, green nanotechnology, and the One Health framework collectively represent a new generation of nanosafety approaches. Rather than responding to hazards after they occur, these strategies emphasize prevention, early detection, and interdisciplinary collaboration throughout the entire life cycle of nanomaterials. Continued integration of computational tools, environmental monitoring, sustainable material design, and global regulatory cooperation will be essential for ensuring that nanotechnology delivers its full societal benefits while protecting human health and the environment.

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