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MINI REVIEW

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Evaluating the toxicological impact of nanoparticles on the environment and human health

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ABSTRACT

The development of nanotechnology has led to the massive production and application of nanoparticles across industrial, biomedical, and environmental sectors. Due to their physicochemical properties, like high surface area, reactivity, and nanoscale dimensions, nanoparticles show improved functional performance. But the release into the environment and human exposure has raised concerns regarding its toxicological impacts. This mini review aims to evaluate the toxicological effects of nanoparticles on both the environment and human health.

Nanoparticles enter the environment through industrial discharge, consumer products, and waste streams, leading to their addition in air, water, and soil systems. Human exposure occurs primarily by inhalation, ingestion, and dermal absorption, causing distribution and cellular interactions. Nanoparticle-induced toxicity is associated with oxidative stress, reactive oxygen species generation, inflammation, and genotoxic effects, which disturb cellular homeostasis and biological pathways. Environmental impacts include adverse effects on aquatic organisms, soil microbiota, and plant systems, with bioaccumulation and trophic transfer.

Despite research, lack of standardized toxicity assessment protocols, variability in experimental models, and challenges in nanoparticle characterization and environmental quantification remains. This mini review mentions the urgent requirement for universal methodologies, improved analytical techniques, and sustainable nanomaterials to regulate potential risks.

KEY WORDS

Nanoparticles; Genotoxic effects; Nanoparticle-induced toxicity; Nanoscale dimension; Inflammation

ARTICLE HISTORY

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Introduction

Nanotechnology has emerged as the most rapidly developing fields in modern science, manipulating molecules at the nanoscale. These happen due to their high surface area-to-volume ratio, enhanced surface reactivity, and quantum effects, which influence optical, electrical, catalytic, and biological behavior. As a result, nanoparticles show improved performance in various applications, including increased chemical activity, increased mechanical strength, and superior functional efficiency [1].

The utility of nanoparticles has led to their widespread application across different sectors such as industry, medicine, agriculture, food technology, and environmental remediation. Engineered nanomaterials, including metal-based nanoparticles, carbon-based nanostructures, and polymeric nanoparticles, are majorly added into consumer products, cosmetics, coatings, pharmaceuticals, and electronic devices. But the large-scale production and use of these materials have resulted in their release into air, water, and soil. These discharges occur through multiple pathways, including industrial effluents, wastewater discharge, and product degradation leading to the nanoparticle accumulation in the environment [2].

With the increasing use of nanoparticles in the environment and their interaction with humans, the nanotoxicology study has gained attention. Nanotoxicology focuses on effects of nanomaterials on biological systems, including humans, animals, plants, and microorganisms. The small size and high reactivity of nanoparticles help them to penetrate biological barriers, and interact with biomolecules, leading to toxic outcomes [3]. Nanoparticle exposure can occur through inhalation, ingestion, and dermal contact, followed by biological distribution within the body. Studies have proved that nanoparticles can induce oxidative stress, inflammation, cellular damage, and genotoxic effects, hence disturbing normal physiological processes. Despite these findings, nanoparticle toxicity remains contradictory. This is due to the lack of standardized experimental protocols, variations in nanoparticle synthesis and characterization, and differences in in vitro and vivo testing models [4].

Nanoparticles have also been reported for negative effects on environmental ecosystems. Their interaction with environmental components can lead to bioaccumulation, trophic transfer, and ecological imbalance. The persistence and mobility of nanoparticles further affect their environmental impact. The mini review aims to evaluate the toxicological impact of nanoparticles on the environment and human health. The review focuses on the sources and pathways of exposure, mechanisms, nanoparticle-induced toxicity, and their effects on biological and ecological systems [5].

Classification and Properties

Nanoparticles are classified based on their composition, origin, and structural characteristics. The most studied categories include metal-based, carbon-based, polymeric, and composite nanoparticles. Metal-based nanoparticles, such as silver (Ag), titanium dioxide (TiO_2), and zinc oxide (ZnO), are used in medical, cosmetic, and industrial applications due to their antimicrobial properties, photocatalytic activity, and stability [6]. These nanoparticles are added into consumer

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products, increasing the chances of environmental release and biological exposure. Carbon-based nanomaterials, including carbon nanotubes (CNTs), fullerenes, and graphene, have mechanical strength, electrical conductivity, and thermal stability, making them useful in electronics, drug delivery, and biosensing applications. Polymeric nanoparticles and dendrimers are used in targeted drug delivery systems due to their biocompatibility and controlled release capacity, while composite nanoparticles combine multiple materials to improve functional performance and stability [7].

The physicochemical properties of nanoparticles influence their behavior in biological and environmental systems. Due to their nanoscale dimensions, nanoparticles have high surface area-to-volume ratio, which improves their chemical reactivity and interaction with biological molecules. Smaller nanoparticles have high mobility, cellular uptake, and reactivity compared to larger particles. Particle shapes as elongated or fibrous structures such as CNTs may induce toxicity like that of fibrous materials like asbestos. Surface charge controls nanoparticle stability, dispersion, and interaction with cellular membranes, while agglomeration and dispersion behavior determine their effective size and bioavailability in different media [8].

Smaller nanoparticles are generally more toxic due to their ability to penetrate biological membranes, interact with intracellular components, and generate reactive oxygen species. Surface chemistry further controls toxicity by protein adsorption, cellular uptake, and immune responses. Also, reactive surfaces induce oxidative stress and cellular damage, leading to major biological effects [9].

Sources and Environmental Release

Natural nanoparticles are generated through various geological, biological, and atmospheric processes. These include volcanic eruptions, forest fires, and weathering of rocks, which produce nanoscale particles that are dispersed into the environment. Also, biological pathways contribute to the nanoparticle formation, such as biogenic magnetite and mineral nanostructures found in living organisms. These naturally occurring nanoparticles have existed for years, and ecosystems have developed adaptive mechanisms [10].

Engineered nanoparticles are synthesized through industrial and laboratory processes for applications. These include metal and metal oxide nanoparticles such as TiO_2, ZnO, and Ag, which are used in cosmetics, pharmaceuticals, food packaging, electronics, and environmental remediation. The increase in industrial production of nanomaterials has contributed to their accumulation in environmental systems. Unlike natural nanoparticles, engineered nanoparticles often possess modified surface properties and enhanced reactivity, which may lead to major interactions with biological and ecological systems [11].

The major sources of environmental contamination by nanoparticles are associated with anthropogenic activities. Industrial discharge is one of the major factor, where nanoparticles are released during manufacturing, processing, and disposal stages. Effluents from industries contain nanomaterial concentrations that are introduced into aquatic systems. Consumer products are also major source of nanoparticle release. Nanoparticles used in cosmetics, sunscreens, coatings, textiles, and personal care products are washed during use, thus entering wastewater streams. Improper disposal of nanoparticle-containing products in landfills results in their gradual leaching into soil and groundwater reserves [12].

Nanoparticles enter and circulate within environment through multiple pathways, including air, water, and soil systems. Atmospheric emissions from industrial activities and combustion processes release airborne nanoparticles, which undergoes long-range transport before deposition. In aquatic systems, nanoparticles are introduced through wastewater discharge, surface runoff, and direct industrial effluents. Soil contamination occurs through sludge disposal, landfill leachates, and deposition from air. Wind dispersion, rainfall runoff, and sedimentation play a crucial role in the redistribution of nanoparticles across different environmental patches [13].

Exposure Pathways

Inhalation is one of the most significant routes, particularly for airborne nanoparticles released from industrial emissions, and combustion processes. Due to their small size, nanoparticles penetrate deep into the respiratory tract and deposit in the alveolar regions of the lungs, where they may induce inflammation and oxidative stress. Ingestion presents another major pathway, causing through contaminated food, drinking water, or indirect consumption by nanoparticle migration from packaging materials. Once ingested, nanoparticles are absorbed through the gastrointestinal tract and enter circulation system. Dermal exposure by nanoparticle-containing cosmetics, sunscreens, and personal care products, where particles penetrate the skin barrier under conditions [14,15].

After entering the body, the distribution and bioavailability of nanoparticles depend on their physicochemical properties, like size, surface characteristics, and solubility. Nanoparticles can be transported by the bloodstream to various organs, including the liver, kidneys, lungs, and brain, where they may accumulate and exert toxic effects. Surface modifications and solubility influence their interaction with biological fluids and cellular components, thereby affecting their bioavailability and persistence within the body [16].

Environmental exposure affects a wide range of organisms across aquatic and terrestrial ecosystems. In aquatic ecosystem, nanoparticles interact with algae, fish, and invertebrates, leading to physiological and biochemical disturbances. In terrestrial environments, soil microorganisms and plants are exposed to nanoparticles through contaminated soil and water. These interactions disrupt microbial activity, nutrient cycling, and plant growth, thus affecting ecosystem functioning. A major concern is their potential for bioaccumulation and biomagnification within the food chain. Nanoparticles can accumulate in organisms at lower trophic levels and subsequently transfer to higher organisms through feeding. This may lead to increased concentration in predators, posing long-term ecological and health risks [17,18].

Mechanisms of Nanoparticle Toxicity

One of the most recognized mechanisms of nanoparticle-induced toxicity is oxidative stress mediated by the generation of reactive oxygen species (ROS). Nanoparticles catalyze the formation of free radicals either directly through surface reactions or indirectly via interactions with cellular components. Excessive ROS production disrupts the cellular redox balance, leading to oxidative damage of lipids, proteins,

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and nucleic acids. Lipid peroxidation compromises membrane integrity, while oxidative DNA damage may result in mutations and impaired cellular function. Metal-based nanoparticles, such as iron and titanium dioxide, are particularly known for their ability to generate hydroxyl radicals through redox cycling reactions, enhancing their toxic potential [19].

At the cellular level, nanoparticles interact with membranes, proteins, and intracellular organelles, leading to structural and functional changes. Due to their small size, nanoparticles can penetrate cell membranes via endocytosis or passive diffusion, causing membrane destabilization and increased permeability. Once internalized, they may interact with proteins and enzymes, altering their structure and function. These interactions can damage biochemical pathways, including mitochondrial activity, leading to energy depletion and apoptosis. Nanoparticle-induced protein denaturation and enzyme inhibition contribute to cellular stress and metabolic imbalance [20].

Genotoxicity and cytotoxicity are associated with nanoparticle exposure. Nanoparticles cause genetic damage through ROS-mediated mechanisms leading to strand breaks, chromosomal aberrations, and mutations, ultimately resulting in cell cycle arrest or apoptosis. Experimental studies have demonstrated that exposure to certain nanoparticles, such as ZnO and CNTs, can reduce cell viability, change cell morphology, and disturb cell cycle processes. These cytotoxic effects are often dose and time dependent, stating the importance of exposure conditions in studying toxicity [21].

Nanoparticles also play a major role in controlling immune responses and inducing inflammation. Their presence in biological systems can trigger the activation of immune cells, leading to the release of pro-inflammatory cytokines and chemokines. This inflammatory response may result in chronic inflammation and tissue damage. The extent and nature of nanoparticle toxicity are strongly influenced by their physicochemical properties. Size-dependent toxicity is significant, as smaller nanoparticles exhibit greater surface area, higher reactivity, and enhanced cellular uptake. Surface modifications, including functionalization and coating, alter nanoparticle stability, dispersion, and interaction with biological molecules, thereby modulating their toxicological profile [22,23].

Impact on Human Health

Respiratory system is one of the primary targets of nanoparticle exposure, particularly through inhalation of airborne particles. Nanoparticles deposit deep within the alveolar regions of the lungs due to their ultrafine size, resulting in prolonged retention and interaction with pulmonary tissues. This induces oxidative stress and inflammatory responses, leading to lung inflammation, fibrosis, and impaired respiratory function. Studies have shown that inhaled nanoparticles show higher deposition efficiency in the lungs compared to larger particles, thus increasing their potential toxicity [24].

Nanoparticles can enter circulation and affect multiple organs, contributing to cardiovascular toxicity. In the bloodstream, nanoparticles interact with endothelial cells, disturb vascular function, and promote oxidative stress, which contribute to cardiovascular disorders. Their accumulation in organs such as the liver, kidneys, and spleen lead to organ-specific toxicity, depending on their physicochemical properties and exposure duration [25].

Nanoparticles are also potential risks to the nervous system. Due to their nanoscale size, certain nanoparticles cross the blood-brain barrier, either through direct translocation or by circulation. This results in neurotoxic effects, including oxidative damage, inflammation, and neuronal dysfunction. Disturbance of neural signalling and cellular homeostasis may cause long-term neurological disorders [26].

TiO_2 and ZnO nanoparticles, widely used in cosmetics and industrial applications, have been associated with oxidative stress, reduced cell viability, and cellular damage. Similarly, CNTs have been reported to induce pulmonary inflammation, fibrosis, and granuloma formation, resembling the effects of fibrous particles. These findings question the understanding of nanoparticle toxicity to ensure safe application and minimize potential health risks [27].

Environmental and Ecological Impact

Aquatic ecosystems are vulnerable to nanoparticle contamination, as many engineered nanomaterials are discharged into water bodies through industrial effluents and wastewater systems. Aquatic organisms such as fish, algae, and microorganisms, have shown oxidative stress, disturbed enzymatic activity, and damaged physiological functions. These changes can lead to impaired growth, reproduction, and survival, affecting aquatic biodiversity [28].

In terrestrial environments, nanoparticles accumulate in soil systems through landfill leachates, wastewater sludge, and atmospheric deposition. Their presence affects plant growth and soil health. Nanoparticles interfere with seed germination, root elongation, and nutrient uptake in plants, changing plant metabolism and productivity. Soil microorganisms, which play a crucial role in nutrient cycling and ecosystem functioning, are highly sensitive to nanoparticle exposure. Disturbing microbial communities can lead to imbalances in soil fertility and ecological stability [29].

Terrestrial organisms, including invertebrates and higher animals, are also affected by nanoparticle exposure. Through direct contact or ingestion of contaminated food and water, nanoparticles can accumulate within tissues and organs. This bioaccumulation can be transferred through the food chain from lower to higher trophic levels [30].

At the ecosystem level, the cumulative effects of nanoparticle exposure result in major ecological disturbances. Changes in species composition, reduced biodiversity, and disruption of ecological interactions are potential outcomes of prolonged nanoparticle contamination. The persistence and mobility of nanoparticles in environment contribute to long-term ecological imbalances, making their impact difficult to predict [31].

Challenges and Limitations

One of the primary challenges is the absence of standardized toxicity testing protocols. Currently, there are no guidelines for evaluating the toxicological effects of nanomaterials, and conventional toxicity assays designed for bulk chemicals are not suitable for nanoscale materials. Another challenge is the assessment of nanoparticle properties such as size, shape, surface charge, and dispersion state for toxicity evaluation. Nanoparticles aggregate in environmental and biological media, changing their effective size and behaviour. The current analytical techniques have limitations in detecting and quantifying nanoparticles in soil, water, and biological tissues. Variations in experimental models contribute to the complexity of nanotoxicology studies. While in vitro models offer rapid and

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cost-effective screening, they may not accurately replicate the complexity of whole-organism responses observed in vivo [32,33].

Future Perspectives

The major research is the design and development of safe nanomaterials through the principles of green nanotechnology. This highlights environmentally friendly synthesis methods, the use of non-toxic precursors, and the reduction of hazardous by-products during nanoparticle fabrication. By using biocompatible coatings and functionalization strategies, it is possible to regulate nanoparticle reactivity and reduce their toxicological impact while maintaining their functional efficiency. Development in toxicity assessment tools is also required for improving the understanding of nanoparticle behaviour. High-throughput screening techniques offer rapid and cost-effective evaluation of multiple nanomaterials under different conditions, ensuring efficient identification of potential hazards. Also, computational modelling and in silico approaches emerge as powerful tools to predict nanoparticle interactions, transport, and toxicity based on physicochemical properties. These methods can reduce dependency on experimental studies and promote predictive risk assessment. The development of standardized testing protocols, validated methodologies, and internationally accepted guidelines will ensure consistent evaluation of nanoparticle toxicity [34,35].

Conclusion

This mini review critically evaluated the toxicological impact of nanoparticles on the environment and human health, with study on exposure pathways, mechanisms, and ecological effects. The study proves that while nanoparticles offer significant technological and industrial advantages, their unique physicochemical properties also contribute to enhanced biological reactivity and potential toxicity. Nanoparticle-induced oxidative stress, cellular disruption, inflammation, and genotoxic effects play central roles in mediating adverse health outcomes. Concurrently, their accumulation in the environment leads to degrading effects on aquatic and terrestrial organisms, with bioaccumulation and ecosystem-level disturbances. Existing limitations, including the lack of standardized toxicity evaluation methods and insufficient data, continue to challenge accurate hazard identification and regulation. Future research should prioritize the development of safer, eco-friendly nanomaterials through green synthesis and surface engineering strategies. Also, research in high-throughput screening, computational toxicology, and standardized regulatory frameworks will be essential for improving risk assessment.

Disclosure Statement

No potential conflict of interest was reported by the author.

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