Innovations in Pharmacy Planet (iP-Planet)
eISSN: 2348 – 7275

Mini Review

Toxicity Profiles of Metal Nanoparticles: Insights from In Vitro and In Vivo Studies

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Abstract
Metal nanoparticles (MNPs) have emerged as transformative tools in various fields, including medicine, electronics, and environmental sciences, owing to their unique physicochemical properties. However, their small size and high reactivity raise concerns about potential toxicological impacts. This review explores the toxicity profiles of widely studied MNPs such as silver, gold, titanium dioxide, and zinc oxide based on in vitro and in vivo studies. The factors influencing toxicity include particle size, surface characteristics, dose, and exposure duration. Mechanisms such as oxidative stress, genotoxicity, and organ accumulation are highlighted. Addressing these risks requires standardized testing protocols, comprehensive long-term studies, and innovative mitigation strategies to ensure safe and sustainable applications of MNPs.

Keywords: Metal nanoparticles, toxicity, oxidative stress, in vitro and in vivo studies, safe applications

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Introduction

Metal nanoparticles are widely used due to their remarkable properties, including high surface-area-to-volume ratios, enhanced reactivity, and unique electronic and optical characteristics. They are integral to sectors like drug delivery, imaging, and environmental remediation. However, their
ability to interact with biological systems at the molecular and cellular levels introduces potential risks. These interactions necessitate an evaluation of their toxicity to mitigate potential adverse effects.[1]

Determinants of Toxicity

The toxicity of metal nanoparticles depends on their size, shape, surface chemistry, and stability. Smaller particles with a high surface-to-volume ratio are more reactive, leading to enhanced biological interactions. Surface modifications, including functionalization, can alter cellular uptake and immune responses. For certain nanoparticles, dissolution and ion release, such as silver and zinc oxide nanoparticles, contribute significantly to toxicity. Aggregation and stability in biological fluids also influence their bioavailability and toxicity profiles.[2]

In Vitro Toxicity Profiles

In vitro studies have demonstrated that MNPs can induce oxidative stress, cytotoxicity, and genotoxicity. The generation of reactive oxygen species (ROS) disrupts cellular redox balance, leading to lipid peroxidation, protein denaturation, and DNA damage. Cellular responses such as apoptosis and mitochondrial dysfunction are common outcomes. DNA strand breaks and chromosomal aberrations have been

reported in studies involving zinc oxide and silver nanoparticles, raising concerns about their genotoxic potential.[3]

In Vivo Toxicity Profiles

Animal studies provide insights into the systemic effects of MNPs, revealing accumulation in organs like the liver, kidneys, and spleen. This accumulation often results in hepatotoxicity, nephrotoxicity, and altered enzyme levels. Immunotoxicity, characterized by cytokine imbalances and inflammatory responses, has also been observed. Furthermore, certain nanoparticles, such as titanium dioxide, have been shown to cross the blood-brain barrier, causing oxidative stress and potential neurotoxicity. These findings underline the importance of assessing long-term and chronic exposure scenarios.[4]

Mechanisms of Toxicity

MNPs exert toxicity through oxidative stress, membrane damage, and mitochondrial dysfunction. The excessive production of ROS disrupts cellular functions, leading to inflammation and tissue damage. Membrane interactions can result in loss of integrity and cell lysis. Mitochondrial disruption affects energy production and initiates apoptotic pathways.[5]

Regulatory Challenges and Research Gaps

The lack of standardized protocols for evaluating the toxicity of nanoparticles poses challenges in comparing study outcomes. Variations in experimental designs, nanoparticle characterization, and dose metrics contribute to inconsistencies. Most studies focus on acute toxicity, with limited exploration of chronic and long-term effects.[6]

Future Perspectives

Developing safer nanoparticles through surface modifications and coatings can reduce toxicity. Advanced testing methods, including high-throughput screening and computational modeling, can improve the prediction of biological interactions. Long-term studies and environmental impact assessments are essential to understand the broader implications of MNPs. Establishing international guidelines for nanoparticle evaluation will enhance data reliability and support safer integration into diverse applications.[7]

Conclusion

Metal nanoparticles offer immense potential across various industries, but their toxicological risks must be thoroughly evaluated. Insights from in vitro and in vivo studies highlight the complexity of their interactions with biological systems. Addressing these challenges through advanced research and regulatory frameworks will ensure the safe and sustainable use of MNPs. Balancing innovation with safety is essential for harnessing their full potential while minimizing adverse outcomes.

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