Analysis of the relationship between nanomaterials and environment

Lu Yu*

Department of Natural Sciences, University College London, London, United Kingdom

*Corresponding author: Zcqslyu@ucl.ac.uk

Abstract. Nanotechnology, a rapidly advancing field, manipulates matter on an atomic scale, offering potential solutions in areas such as environmental remediation, energy storage, and pollution control. However, introducing engineered nanomaterials (ENMs) like carbon nanotubes and metal oxides raises concerns due to their potential environmental and health impacts. ENMs have effectively removed pollutants from water, air, and soil, with materials like nanoscale zero-valent iron and titanium dioxide excelling in remediation efforts. Despite these benefits, the environmental risks posed by nanoparticles, such as bioaccumulation, toxicity to aquatic organisms, and respiratory hazards, remain significant. The persistence of certain nanomaterials, coupled with insufficient data on their long-term behaviors, exacerbates these concerns. This research will explore the positive and negative impacts of ENMs on the environment, discuss the different impacts brought by different nanomaterials in the four articles, and emphasize the importance of developing green nanotechnology solutions. Analyzing the role of nanomaterials in the environment is to strike a balance between innovation and safety, minimizing the environmental footprint while maximizing the benefits.

Keywords: nanomaterials; environment; interaction relationship.

1. Introduction

The invention of nanotechnology has brought new scientific and technological breakthroughs to the world, is the science of manipulating matter on the atomic and molecular scale and can contribute to various industries, from medical technology to energy, from electronics to engineering. Nanotechnology has become the innovation potential. However, there are advantages and disadvantages to nanotechnology, and a need to pay attention to the impact of nanotechnology on the environment. There is a major debate among scientists, policymakers and environmentalists about nanotechnology, especially introducing engineered nanomaterials (ENMs) into ecosystems.

This technology has introduced substantial innovations across numerous industries, including environmental remediation, energy, and pollution control. For example, four ENMs utilized in environmental applications are silver nanoparticles (AgNPs), titanium dioxide ($nTiO_2$), zinc oxide (ZnO), and nano zero-valent iron (nZVI). Each of these materials exhibits specific functionalities that make them effective in addressing pollution and improving environmental health.

AgNPs, widely known for their antimicrobial properties, are frequently used in water treatment and disinfection. $nTiO_2$, with its photocatalytic abilities, is employed in air and water purification, breaking down organic pollutants under light. ZnO is another photocatalytic material, often used in removing contaminants from water sources and air. nZVI is primarily applied in soil and groundwater remediation, effectively reducing toxic substances such as chlorinated solvents. These materials share common traits—high surface area and reactivity—enabling them to efficiently target and neutralize pollutants, making them indispensable for sustainable environmental practices.

One of the most promising applications of nanotechnology lies in environmental remediation. Nanomaterials such as carbon nanotubes, metal oxides, and nanoparticles have shown remarkable efficiency in removing pollutants from water, air, and soil. For instance, nZVI particles are widely used in the remediation of contaminated groundwater, effectively reducing toxic heavy metals and organic pollutants [1]. TiO_2 nanoparticles are employed in photocatalytic processes to degrade

harmful organic compounds in wastewater [2]. These applications not only enhance the efficiency of pollution control but also contribute to the development of sustainable environmental practices.

Despite the many benefits of nanotechnology, the risks it poses to the environment cannot be ignored. The production, use, and disposal of nanomaterials pose potential threats to ecosystems and human health. Nanoparticles, due to their small size and high reactivity, can easily penetrate biological membranes and accumulate in living organisms, leading to toxicological effects. AgNPs, commonly used for their antimicrobial properties, can cause oxidative stress and damage to aquatic organisms [3]. The persistence of certain nanomaterials in the environment raises concerns about their long-term ecological impact, as they may not degrade easily and could potentially bio-accumulate in the food chain.

The shared characteristics of these nanomaterials, such as their nanoscale size and high reactivity, make them particularly effective in interacting with pollutants at a molecular level. They enhance pollution control mechanisms by offering vast surface areas for adsorption and catalytic degradation, allowing for the breakdown of harmful compounds. While these materials provide significant environmental benefits, including improved air and water quality and more efficient soil remediation, their potential risks, such as toxicity and bioaccumulation, must be considered. The unique properties that enable these nanomaterials to address environmental challenges can also lead to adverse effects if not managed properly, highlighting the need for continued research into their safe and responsible use [4].

This research will discuss the specific role of nanomaterials in the environment. With nanotechnology offers significant opportunities to improve the environment, it also poses risks to the environment. The future of nanotechnology in environmental applications will depend on continued research into its safety, the development of green nanotechnology practices, and the implementation of robust regulatory frameworks. For future research and development goals, research should be on new, harmless nanomaterials, and the goal should be to harness the power of nanotechnology to create a sustainable future while protecting the health of our planet and its inhabitants.

2. The relationship between nanomaterials and environment

2.1. Effect of nanotechnology on the environment

Various nanomaterials, including ENMs like SiO_2, TiO_2, FeOx, AlOx, ZnO, and CeO_2 nanoparticles has been discussed [4]. These materials are chosen for their unique physical properties, such as high surface area, reactivity, and strength. Nanostructured electrode materials are used to improve lithium-ion batteries, and TiO_2 nanoparticles are used for photo-catalytic applications like self-cleaning surfaces.

Nanomaterials can have both positive and negative environmental impacts. Positively, nanomaterials help address pollution, improve industrial processes, and offer applications in water treatment, air purification, and energy storage. However, due to their small size, nanoparticles can be harmful when released into the environment. Their interaction with living organisms and ecosystems remains a concern due to the potential for toxicological effects, especially when considering chemical composition, size, and shape.

The potential risks of nanoparticle release from production, use, and disposal processes has been analyzed. Nanomaterials can spread through the air, be transported in water, or accumulate in soil, which raises concerns about bioaccumulation and toxicity in these environments. For air, nanoparticles can be emitted into the atmosphere during production, transportation, and disposal. Once in the atmosphere, nanoparticles may aggregate, attach to other particles, or remain suspended, leading to potential inhalation risks for humans and animals. The mobility of nanoparticles in the air allows them to travel long distances, potentially reaching sensitive environments far from their source. For water, nanoparticles can enter water systems through direct release or indirectly via runoff from industrial and urban sources, wastewater treatment plants, or aerial deposition (falling from the atmosphere). The impact on aquatic life can be caused by the ability of nanoparticles to bioaccumulate

in aquatic organisms raises concerns. Fish and other aquatic species may absorb nanoparticles directly from the water, or through the food chain, as they ingest contaminated plants or smaller organisms. The risk increases when nanoparticles aggregate, as they may settle into sediments or be absorbed by filter-feeding animals. Nanoparticles can also accumulate in soil, either through direct deposition from atmospheric particles or because of contaminated water entering the soil. This is particularly concerning for agricultural areas where nanoparticles could enter the food chain through plants. Nanoparticles in soil can interact with microorganisms, plants, and animals. For example, plants may take up nanoparticles through their roots, leading to the accumulation of these materials in crops. Nanoparticles can either remain in the soil or be transported through soil layers via water flow, potentially affecting groundwater systems.

Nanoparticles are highly mobile and can be transported by air, water, or through biological systems. Their behavior in the environment depends on their chemical composition, size, and surface properties. Hydrophobic nanoparticles might aggregate in water, while hydrophilic ones might dissolve, making them harder to filter out. Nanoparticles can contaminate different environmental mediums due to their high reactivity and surface area. Their ability to interact with other chemicals, organic compounds, or pollutants can either enhance or hinder environmental recovery processes, depending on how they are used or disposed of.

There are some potential risks for the environment when using nanomaterials. The risk of respiratory exposure to nanoparticles can cause health issues when inhaled. Particles that remain airborne for extended periods can penetrate deep into the lungs, potentially leading to chronic respiratory conditions or other health effects. In water, nanoparticles pose a risk due to their potential toxicity to aquatic organisms. They can interfere with water quality and ecosystems, with the ability to accumulate in fish, plants, and microorganisms. The presence of nanoparticles in soil can alter the natural balance of microbial communities, affect plant growth, and lead to the bioaccumulation of harmful particles in crops, which could then enter the human food chain.

The lack of comprehensive data on nanoparticle behavior in these environments is a significant challenge. While nanotechnology offers promising solutions for pollution control and resource efficiency, the risks posed by uncontrolled release and improper disposal of nanomaterials are not yet fully understood. As a result, these environmental systems require careful monitoring and regulation to prevent unintended harm.

For good and bad aspects of nanomaterials, the positive aspects of nanomaterials are that nanotechnology improves energy efficiency, and pollution control, and reduces waste. It enhances material strength and longevity, allowing for better performance in applications like solar cells and wind turbines. Nanomaterials are also effective in environmental remediation, such as cleaning up heavy metals from wastewater or contaminants in industrial sites. However, the primary concerns include the potential toxicity of nanoparticles to both humans and the environment. Nanoparticles are difficult to monitor and assess due to their small size and variability in chemical properties. There are also high energy costs associated with the production of nanoparticles, along with challenges in recycling and managing nanomaterial waste.

The effects of nanomaterials are heavily influenced by their surface area, reactivity, and interactions with biological systems. Nanoparticles have higher surface areas than bulk materials, which can result in greater toxicity. The lack of comprehensive methods to assess nanoparticle toxicity and environmental behavior complicates the risk assessment. There is the need for lifecycle analyses to accurately evaluate the risks and benefits of nanomaterials, ensuring that their environmental impact is minimized.

2.2. Trends, risks and opportunities in environmental nanotechnology

For metallic nanoparticles, such as AgNPs, $nTiO_2$, nZnO, and iron or iron oxide nanoparticles, these materials exhibit high surface area, reactivity, and specific functionalities due to their nanoscale size. Carbon-based nanomaterials, like graphene, graphene oxide (GO), and carbon nanotubes (CNTs) are highlighted for their use in sensing, catalysis, and energy applications. For hybrid ENMs, these

include nanocomposites designed for multifunctionality, combining properties such as adsorption and catalytic degradation. The properties of these materials make them useful for environmental applications like water treatment, soil remediation, and air pollution control. Their small size (1–100 nm), high reactivity, and unique surface properties due to quantum effects enable them to interact with pollutants effectively.

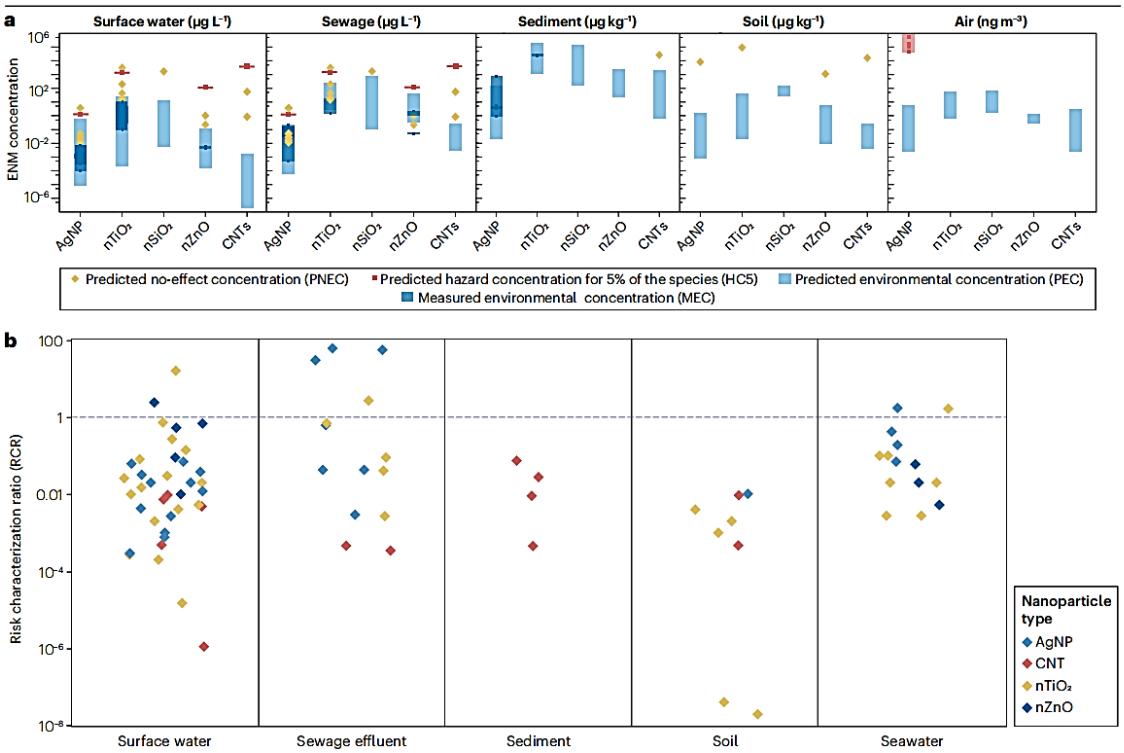


Fig. 1 Concentrations and risk characterization ratios of selected ENMs. (a) The selected ENMs concentrations for different environmental compartments. (b) Risk characterization ratios (RCRs) for the same environmental compartments, which is the PEC to PNEC ratio of a specific ENMs [5].

When ENMs are released into the environment, it can reduce their bioavailability and reactivity, thereby decreasing their potential toxicity. ENMs are applied for water treatment, including membrane separation, photocatalysis, and pollutant removal. The ENMs provide high surface area and active sites for adsorption and catalytic degradation, particularly in treating water contaminated with heavy metals or organic pollutants. ENMs like $nTiO_2$ are used for air purification through photocatalytic processes to degrade volatile organic compounds. ENMs are employed for soil remediation, particularly for heavy metal decontamination. nZVI is highlighted for groundwater treatment to remove pollutants like chlorinated solvents.

There are also some potential risks that the article primarily studies the impact of ENMs in water, air, and soil environments [5], as shown in Fig, 1. Key risks include the potential release of ENMs into water systems. During production, use, or disposal, leading to bioaccumulation in aquatic organisms and contamination of drinking water sources. The airborne risks of inhalation, particularly during ENM production, can lead to pulmonary toxicity due to ultra-fine particles penetrating deep into the lungs. Soil contamination and potential bioaccumulation of ENMs in plants and animals can enter the human food chain. Passivating transformations (e.g. oxidation, sulfidation, aggregation) typically reduce the environmental risks of ENMs. However, localized risks may arise near point sources like sewage effluent, where higher concentrations of ENMs can occur.

For positive aspects, ENMs offer significant environmental benefits by improving pollution control, enabling cleaner industrial processes, and enhancing water and air quality. They also contribute to sustainability through the removal of pollutants, such as heavy metals, from contaminated water and soil, and by reducing greenhouse gas emissions through catalytic processes. The ability to fictionalize ENMs allows for the selective removal of pollutants like nitrous oxide or

organic contaminants. For negative aspects, high energy costs are associated with the production of ENMs, and the synthesis process can lead to environmental harm due to toxic emissions. There is uncertainty about the long-term environmental impact of low concentrations of ENMs, particularly regarding their accumulation in water bodies and soil. Potential toxicity to human health, particularly through inhalation during manufacturing, remains a concern. Additionally, bioaccumulation in ecosystems could pose long-term risks.

The passivation and transformation processes of ENMs in the environment, such as aggregation, surface oxidation, and sulfidation reactions, reduce their reactivity and toxicity. These processes lower the bioavailability of ENMs, decreasing their harmful effects on ecosystems. However, life-cycle analysis (LCA) shows that the highest environmental and health risks are associated with ENM production, rather than incidental release during use. Detected concentrations of ENMs in the environment are typically 1 to 4 orders of magnitude lower than predicted no-effect concentrations (PNECs). For example, measured environmental concentrations (MECs) of AgNPs and $nTiO_2$ are generally much lower than the predicted hazardous levels in surface water, air, and soil. However, higher risks are noted in sewage effluent, where ENM concentrations may exceed safe thresholds [5]. ENMs offer significant environmental benefits, particularly in pollution control and water treatment, but their safe use depends on careful management of production, disposal, and long-term environmental monitoring.

2.3. Evaluating nanotechnology opportunities and risks through the integration of life-cycle and risk assessment

ENMs are used in emerging technologies such as solar photovoltaics and lightweight, strong materials for aircraft. Key properties include high surface area, increased reactivity, and novel quantum behaviours that distinguish them from bulk materials. For example, carbon nanotubes and $nTiO_2$ are frequently mentioned for their strength, reactivity, and ability to enhance energy storage or improve pollution control systems.

The impact of nanomaterials of ENMs across various stages of their life cycle, from production to disposal, including their release into the environment. For ecological systems, the ENMs are assessed for their impact on air, water, and soil environments through potential emissions during their life cycle. They can bioaccumulate and pose risks to aquatic life, plants, and soil organisms. For human health, nanomaterials may pose risks to human health, particularly for occupational exposure during manufacturing and for consumers using products that contain ENMs.

For some environmental studies and potential risks, it studied the impacts of ENMs in occupational and natural environments, focusing on potential risks such as air, water, soil and life cycle. There are some concerns about air, especially inhalation risks. During the production or handling of ENMs in manufacturing settings, nanoparticles can remain airborne, potentially leading to lung toxicity or other respiratory issues for workers. For water, ENMs can enter water systems through industrial waste or runoff, leading to potential contamination of drinking water and bioaccumulation in aquatic organisms. In soil, ENMs can interact with plant roots and microbes, potentially affecting agriculture and ecosystems. The highest environmental risks in the life cycle are associated with the production phase, where energy use and emissions are significant. The release of ENMs into ecosystems during their use or disposal is of concern, especially if they aggregate, accumulate, or undergo chemical transformations that increase their toxicity.

There are some positive aspects of nanomaterials. Firstly, ENMs offer significant environmental benefits through their applications in renewable energy, pollution control, and material efficiency [6]. Secondly, they can help reduce greenhouse gas emissions by improving energy efficiency and supporting clean energy technologies. Thirdly, the article emphasizes the potential resource efficiency that ENMs provide, helping industries become more sustainable through better materials and reduced waste. Also, there are some negative aspects, ENMs carry toxicity risks due to their high reactivity and small size. They can penetrate cells, leading to oxidative stress, cytotoxicity, or genotoxicity, especially if inhaled or ingested in large quantities. In addition, life cycle impacts show that the energy

costs of producing ENMs are high, and their disposal poses a risk of contamination in air, water, and soil environments. There is a lack of comprehensive data on long-term exposure effects, particularly concerning their transformation in the environment, which could make them more hazardous over time.

LCA and risk assessment (RA) tools can be used to evaluate the environmental and human health impacts of nanomaterials, as shown in Fig. 2. These methods provide a comprehensive view of how ENMs behave throughout their life cycle and allow for comparisons between their potential benefits and risks. LCA analyzes the resources, energy use, and emissions associated with ENMs from production to disposal. It shows that most of the environmental impact comes from the production phase due to high energy consumption and resource extraction. However, emissions during use and disposal are typically lower. RA focuses on the toxicological risks posed by ENMs when released into the environment. The analysis shows that while the concentration of ENMs in the environment is generally low, localized risks may exist near point sources like industrial facilities. Statistical models in the article suggest that ENM-related risks are concentration-dependent and vary across different environments. ENMs present both significant opportunities and challenges in terms of environmental safety. Their unique properties can drive technological innovation and resource efficiency, but they also pose risks to human health and the environment, particularly during production and disposal.

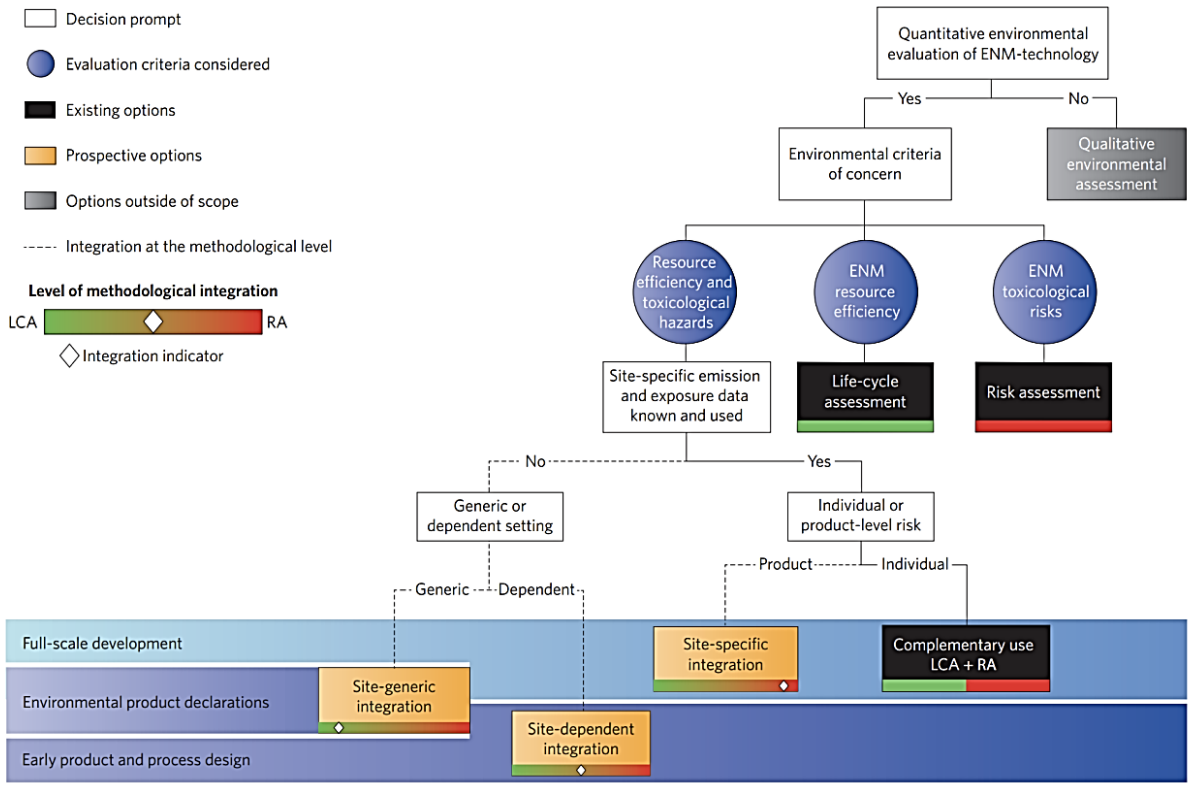


Fig. 2 Two separate, one complementary and three integrated options for using of LCA and RA to evaluate nanotechnologies [6].

2.4. Advanced tools for the safety assessment of nanomaterials

Key material properties highlighted are their size, surface area, shape, and reactivity, which significantly influence their behaviour in biological systems and the environment. These properties also make ENMs highly versatile for applications like sensors, drug delivery, and environmental remediation. Additionally, synthetic and context-dependent properties of ENMs, such as their interaction with proteins or other biomolecules, impact their toxicity and environmental fate.

The impact of ENMs is evaluated through in vitro, in vivo, and computational models to understand their cytotoxicity, genotoxicity, and immunotoxicity. ENMs can cause cellular damage,

oxidative stress, and inflammation, with potential implications for both ecosystems and human health. The article highlights the need for accurate prediction models that integrate LCA and RA to evaluate the impact of ENMs across their life cycle.

For air, the release of ENMs during production processes can lead to inhalation exposure in industrial settings. ENMs in aerosol form pose risks to respiratory health, particularly in confined spaces or workplaces with poor ventilation. For water, the ENMs released into water bodies (through industrial runoff or improper disposal) can bioaccumulate in aquatic organisms, affecting both ecosystems and human consumers through the food chain. For soil, ENMs can interact with microbial communities and plants, potentially leading to long-term ecological effects. The risks of bioaccumulation and toxicity associated with persistent ENMs in various environments are analyzed, raising concerns about their long-term environmental sustainability and safety.

For positive aspects, ENMs enable innovations in medicine, energy, and environmental applications, offering benefits like enhanced drug delivery, pollution remediation, and energy-efficient devices. They contribute to sustainability by improving resource efficiency and reducing waste in certain processes. For instance, ENMs can enhance the performance of solar panels and reduce energy consumption in manufacturing. For negative aspects, toxicological risks are a major concern, especially for workers handling ENMs. ENMs may cause cellular damage, oxidative stress, and chronic health issues if inhaled or ingested. For environmental persistence, ENMs, once released, may persist in the environment, accumulating in soil or water systems, leading to potential ecological disruptions. The high energy costs and environmental impacts associated with the production of ENMs may offset some of their environmental benefits.

It also discussed that the toxicological effects of ENMs are influenced by their physicochemical properties, such as size, shape, surface charge, and aggregation behavior. For instance, smaller particles with high surface reactivity are more likely to penetrate cells and cause oxidative damage. Statistical models from high-throughput screening (HTS) and systems biology approaches are used to predict the toxicity of ENMs based on these properties. Omics data is increasingly used to identify biological pathways affected by ENMs, improving the understanding of their mode of action. LCA and RA help quantify the overall impact of ENMs by comparing their environmental and health risks across different stages of their life cycle, from production to disposal. Data gaps in exposure scenarios and long-term environmental behavior complicate the assessment of ENM risks, but new tools and models are being developed to bridge these gaps [7].

ENMs offer significant technological advancements, and their environmental and health impacts require careful management. Integrating advanced tools for risk and safety assessment can improve the understanding of how ENMs behave in real-world scenarios, helping mitigate potential risks and promote safer, more sustainable nanotechnology applications.

3. Conclusion

Nanotechnology holds vast potential to address environmental challenges through innovations in pollution control, energy efficiency, and resource management. However, the associated risks, particularly the toxicity and persistence of ENMs in ecosystems, cannot be overlooked. The research highlights the dual nature of nanotechnology's environmental impact, where the benefits of advanced nanomaterials are tempered by concerns over their safe use, disposal, and long-term ecological effects. A balanced approach is essential, emphasizing the development of green nanotechnology practices and stricter regulatory frameworks. Ongoing research into the safety and sustainability of nanomaterials is critical to harnessing their benefits while minimizing their environmental risks.

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