International Journal of Applied Science
ISSN (Online): 2208-2182
Volume 11 Issue 02-June, 2025

DOI: https://doi.org/10.53555/qh2hm214

NANOTECHNOLOGY'S DUAL EDGE: EVALUATING HEALTH AND ENVIRONMENTAL CONSEQUENCES OF ENGINEERED NANOMATERIALS

Md Afzal Mansoori[1*], Khushboo Mishra[2], Binay Kumar Mishra[3]

[1*]*Research Scholar, Department of Physics, Veer Kunwar Singh University Ara -802301, India, mdafzalmansoori@gmail.com*
[2]*Research Scholar, Department of Physics, Veer Kunwar Singh University Ara-802301, India, Kmishra.j94@gmail.com*
[3]*Professor, Department of Physics, Veer Kunwar Singh University Ara -802301, India, drmishrabinay@gmail.com*

Corresponding Author:
**Email: mdafzalmansoori@gmail.com*

Abstract

The quick development of nanotechnology is reflected in the expanding use of engineered nanomaterials (ENMs) in industries including electronics, environmental sciences, and medicine. Although these materials have the potential to be revolutionary, their special qualities also pose serious questions about environmental safety and human health. With an emphasis on how ENMs interact with biological systems and environmental matrices, this review evaluates the toxicological and ecological effects of ENMs. The objectives include evaluating mechanisms of cytotoxicity, genotoxicity, and oxidative stress, examining bioaccumulation and persistence in ecosystems, and reviewing current risk assessment strategies. A systematic review of recent peer-reviewed studies, regulatory guidelines, and toxicological data was conducted. Evidence suggests that ENMs exhibit physicochemical traits that enhance their functional value but can also lead to biological disruption. Their ability to penetrate cellular barriers, induce oxidative stress, and interfere with physiological processes raises significant safety concerns. In environmental contexts, ENM accumulation is linked to microbial imbalance and ecological toxicity. The review underscores the urgency of developing harmonized safety protocols, eco-friendly synthesis techniques, and comprehensive regulations to mitigate risks. Future research should prioritize green nanotechnology and safer-by-design principles to promote responsible innovation.

Keywords: *Nanotoxicology, engineered nanomaterials, environmental impact, risk assessment, oxidative stress, green nanotechnology.*

I. Introduction

1. Background on Nanotechnology

Nanotechnology is the research, development, and production of devices that are one to one hundred nanometers in size. The surfaces of solid materials at this scale have very different physicochemical properties from their bulk. Such differences are characterized by an increment of surface area, reactivity, and mechanical strength (Brune et al., 2006). There are several applications for nanotechnology, including electronics, agriculture, environmental cleanup, and medicine. Richard Feynman, a physicist, first proposed the idea of nanotechnology in his 1959 speech, "There is Plenty of Room at the Bottom," in which he proposed that materials at the nanoscale may be created by manipulating individual atoms (Brune et al., 2006). The development of engineered nanomaterials (ENMs) accelerated in the following decades after the discovery of scanning tunneling microscopy (STM) and atomic force microscopy (AFM), which allowed scientists to view and manipulate atoms at the nanoscale level (Brune et al., 2006; Clunan & Rodine Hardy, 2014).

ENMs are currently synthesized in many forms, including carbon-based materials (e.g., fullerenes and carbon nanotubes), metal and metal oxide nanoparticles (e.g., silver, gold, and titanium dioxide), polymeric nanomaterials, and quantum dots. All these materials have unique properties that render them suitable for use in various industrial and biomedical applications (Gajewicz et al., 2012). They have studied their application in drug delivery, biosensing, catalysis, water purification, and advanced coatings because of their outstanding functional properties (Malik et al., 2023). Nevertheless, their high usage in the manufacture of consumer products has brought about issues that are related to their possible health and environmental effects (Wahab et al.,2024).

2. The Dual Nature of Nanotechnology

It is not a secret that nanotechnology can transform industries by enhancing the performance of products, revolutionizing healthcare interventions, and responding to environmental problems. On the one hand, however, they have numerous benefits, but they also provoke more and more alarming responses, that is, about their unintended effects on human health and ecological systems (Albrecht et al.,2006). The two-sided aspect of nanotechnology, with its huge potential benefits and possible risks, may be represented in Figure 1, which reflects various applications of nanotechnology and related concerns.

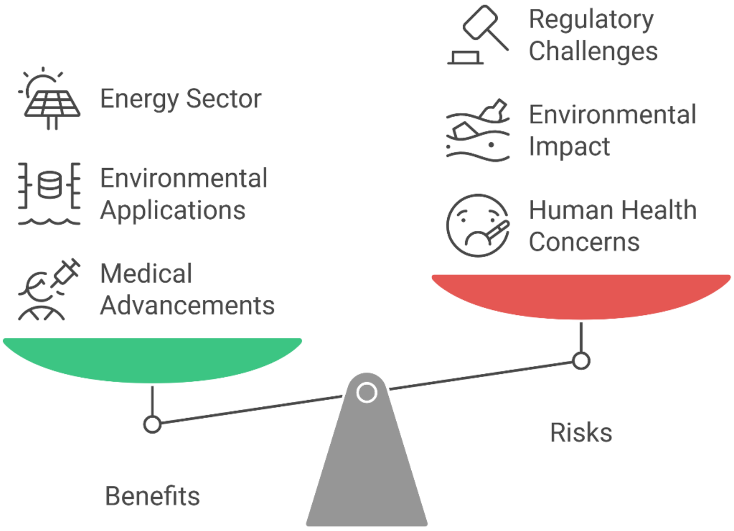

Figure 1: The Dual Nature of Nanotechnology

Benefits of ENMs in Various Industries

ENMs have been incorporated in different industries, which have a great influence on technological developments. The development of targeted drug delivery systems, in which therapeutic drugs are delivered to damaged tissues using nanoparticles, is one use of nanotechnology that shows promise for the medical field (Albrecht et al.,2006). The approach decreases the systemic toxicity of overall treatment and enhances its efficacy (Malik et al., 2023). In addition, ENMs find applications in diagnostic imaging, regenerative medicine, and the development of biosensors, which enable diagnosis of the disease at an early age and deliver personalized medication (Ma et al., 2024).

Nanomaterials enhance electronics applications in the electronics industry in terms of enhancing the improvement of semiconductor performance and the capability of developing smaller, faster, efficient devices that consume less energy using semiconductors (Brune et al., 2006). They can also be used to access renewable energy sources, and they enhance the energy density of energy storage technologies (i.e., batteries and supercapacitors), making energy storage charging capabilities more suitable to their needs (Huang et al., 2024).

Moreover, titanium dioxide (TiO2) and silver nanoparticles have also been utilized in the process of degrading pollutants and the antimicrobial action segment of water treatment processes, and the benefits to the environment are exposed (Nel et al.,1970). It is also through nanotechnology that sustainable agricultural practice can be improved by coming up with nano fertilizers and nano pesticides that could increase the productivity of crops and reduce chemical runoff (Albrecht et al.,2006).

Potential Risks and Concerns

Although there is an acknowledged benefit of engineered nanomaterials (ENMs), their relevance has not been much exploited for fear that the material may be potentially unsafe and indestructible in the environment. Thanks to their small size and considerable surface reactivity, nanoparticles can penetrate living cells, remain in the body, and cause toxic effects in cells (Ganguly et al., 2018). As research indicates, ENMs are apt to produce reactive oxygen species (ROS), which may produce oxidative stress, damage DNA, and inflammatory conditions in organisms that they interact with (Hristozov & Malsch, 2009).

Pulmonary toxicity, systemic immunological reactions of inflammation, and fibrosis have also been documented to be a result of exposure to nanoparticles even in occupations in human beings (Warheit et al., 2008). In addition, BFRs contaminate the human body through consumer products, i.e., cosmetics and food wrappings which raises a question on the long-term exposure and the potential health consequences (Chen & Chen, 2017).

In ecology terms, the release of ENMs in the water bodies and soil can be disastrous to our biodiversity. The nanoparticles may gather in the water bodies and influence the aquatic organisms at various levels of trophic levels (Hristozov & Malsch, 2009). To illustrate, silver and zinc oxide are nanoparticles of metal-based nanoparticles, with antimicrobial effects that may disrupt microbial life, causing the development of antimicrobial resistance (Corsi et al., 2023). In addition, the sustained presence of ENMs in the soil can also disturb nutrient ratios, stall the growth of plants, and lead to long-term implications on the sustainability of agriculture (Shukla et al., 2024).

The fact that nanotechnology is a technology which, on the one hand, can bring about amazing benefits and, on the other hand, introduce some risks to it demands the need to have a balanced approach to its development and application (Wahab et al.,2024). It is necessary to understand these risks to have in place regulatory mechanisms and mitigation measures that can result in the safe and sustainable use of ENMs.

Objectives of the Review

- Evaluate health implications of ENMs: Nanotoxicity process, oxidative stress, DNA damage, inflammatory responses, systemic effects on pulmonary, cardiovascular, and neurological health.
- Examining the environmental impact of ENMs: Analyzing ENMs' persistence, bioaccumulation, and ecotoxicological impacts in aquatic and terrestrial ecosystems is necessary. These effects include microbial function disruption, biodiversity loss, and environmental contamination.
- To suggest regulation and mitigation methods for the responsible production of ENMs, examine existing risk assessment techniques, global regulatory frameworks, and sustainable nanotechnology approaches, such as green synthesis and safer-by-design initiatives.

II. Classification and Properties of Engineered Nanomaterials

1. Types of Engineered Nanomaterials (ENMs)

The compositions and structures of ENMs are diverse and allow their application in many industries. It is categorized chemically and by its functional properties.

- ENMs of carbon-based: It can be something like carbon nanotubes (CNT) and graphene. CNTs have extraordinary sturdiness, electrical conduction, and chemical stability, and they can be utilized in electronics, energy storage, and biomedical applications (Brune et al., 2006). This nanomaterial, Graphene, occurs as a two-dimensional nanomaterial with high surface area, exceptional thermal conductivity, and mechanical flexibility, and therefore, graphene can be applied for biosensors, drug delivery, and filtration systems (Singh et al., 2024).
- Nanoparticles of silver, gold, titanium dioxide, and zinc oxide: As these nanoparticles show antibacterial, catalytic, as well as optical properties, they are widely used (Ganguly et al., 2018). AuNPs are employed as drug carriers and imaging agents in biomedical applications, whereas AgNPs are extensively utilized in antimicrobial coatings, medical equipment, and wound dressings (Hristozov & Malsch, 2009). Zinc oxide (ZnO) and titanium dioxide (TiO2) nanoparticles are widely used in sunscreens, cosmetics, and environmental remediation due to their photocatalytic and UV-blocking qualities (Albrecht et al.,2006).
- Quantum dots (QDs): Semiconductor nanoparticles demonstrate unique optical characteristics because of quantum confinement effects. On account of their tunable fluorescence, they serve as valuable bioimages, medical diagnostics, and optical electronics (Ma et al., 2024). However, safety issues have indeed been raised on account of their potential cytotoxicity and heavy metal content (Gajewicz et al., 2012).
- Biodegradable polymeric nanoparticles: Most biodegradable polymeric nanoparticles are prepared from biodegradable polymers, mainly Poly (lactic-co-glycolic acid) (PLGA), PEG, and chitosan. Sustained drug release and improved biocompatibility make them commonly used in controlled drug delivery and vaccine development (Malik et al., 2023).
- "Lipid-based nanoparticles are liposomes and solid lipid nanoparticles (SLNs)", which have been explored for encapsulation of hydrophobic drugs and also to enhance bioavailability (Malakar et al., 2021). Among all lipid-based carriers, they have a good ability to promote cellular uptake without inducing significant toxicity and, therefore widely used in formulations of vaccines, which contain vaccines such as mRNA-based vaccines (Nel et al.,1970). The classification and properties of engineered nanomaterials is mentioned in Table 2.

Table 1: Classification and Properties of Engineered Nanomaterials (ENMs)

Type of ENM	Composition	Key Properties	Applications
Carbon-based ENMs	Carbon nanotubes (CNTs), Graphene	High mechanical strength, electrical conductivity	Electronics, energy storage, biosensors
Metal & Metal Oxide Nanoparticles	Silver (Ag), Gold (Au), Titanium dioxide (TiO_2)	Antimicrobial, catalytic, UV-blocking	Medical coatings, sensors, and sunscreens
Quantum Dots (QDs)	Semiconductor nanoparticles	Tunable fluorescence, bio-imaging	Medical diagnostics, optical devices
Biodegradable Polymeric Nanoparticles	PLGA, PEG, Chitosan	Biodegradable, sustained drug release	Drug delivery, vaccine development
Lipid-based Nanoparticles	Liposomes, Solid Lipid Nanoparticles (SLNs)	Encapsulation of hydrophobic drugs, enhanced bioavailability	mRNA vaccines, pharmaceuticals

2. Physicochemical Properties and Their Relevance

Physicochemical properties dictate the unique behavior of ENMs, given their capability to interact with biological systems as well as environmental matrices.

- Reactivity and bioactivity: The nanoscale size, shape, and surface area are important for any purpose of ENMs. Smaller nanoparticles can interact with more biological molecules and cells because of their larger surface area to volume ratio (Warheit et al., 2008). Ganguly et al. (2018) have reported that nanoparticles of spherical shape differ in cellular uptake pattern from rod-shaped as well as nanoparticles of irregular shapes, which further influence their biodistribution and toxicity.
- Nanoparticle surface charge and reactivity: This nanoparticle's zeta potential is what determines how stable the particles are in biological and environmental systems. Positively charged nanoparticles are more likely to be drawn to the cell membrane's negative charges, which might increase their cytotoxicity (Teow et al., 2011). For instance, PEGylated nanocarriers are functionalized nanoparticles that can decrease the immune recognition and extent of bloodstream circulation (Nel et al.,1970).
- Bioavailability and persistence: The solubility, aggregation behavior, and degradation mechanisms of ENMs determine their persistence in biological systems and environments. But other metal nanoparticles, such as silver and titanium dioxide, have limited biodegradability and are not biodegradable, which might cause them to accumulate over time and have an adverse effect on the environment (Corsi et al., 2023).

III. Health Implications of Engineered Nanomaterials

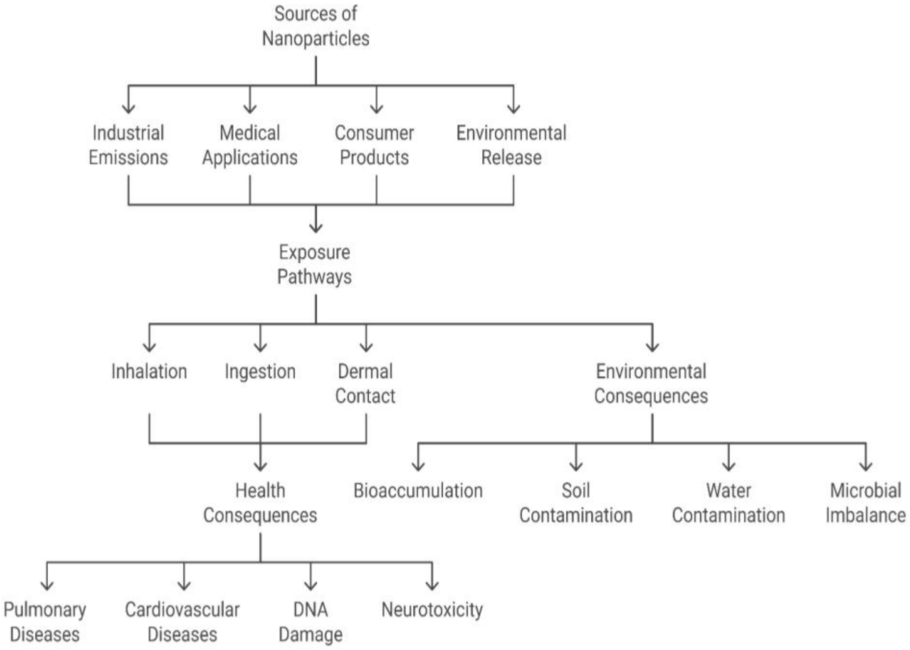

Figure 2: Pathways of Nanoparticle Exposure and Impact

Figure 2 illustrates the various pathways through which engineered nanomaterials (ENMs) enter biological systems and the environment, leading to potential health and ecological consequences.

Engineered nanomaterials (ENMs) may gain access into human body via various exposure channels and can interfere with biological systems such that they are likely to cause negative health effects. This section describes the toxicokinetics, cellular interactions and systemic health effects of ENMs with emphasizing the recent toxicological data.

1. Pathways of Exposure and Toxicokinetics

The exposure pathways to engineered nanoparticles (ENMs) are multiple and may include inhalation, ingestion, contact via the skin, or intravenous injection. Of them, the inhalation of airborne nanoparticles is supposed to be especially dangerous as they are likely to accumulate deep in the lungs, which can result in inflammation and respiratory problems (Warheit et al., 2008). Nanoparticles can circulate in the body and access different organs such as the liver, kidney, spleen, and even the brain once they are in the body. It is also possible that some ENMs can pass through the blood-brain barrier, which brings up the issue of neurotoxicity (Ma et al., 2024). The metabolism and excretion of ENMs are quite different; some of them can be excreted with urine or feces, whereas others cannot be rapidly biodegraded and can accumulate in the body (Ganguly et al., 2018).

2. Cytotoxicity and Genotoxicity Mechanisms

One of the key mechanisms influencing the toxicity of engineered nanomaterials (ENMs) is the production of reactive oxygen species (ROS). According to Gajewicz et al. (2012), the generation may lead to anomalies in proteins, mitochondria, lipid peroxidation, and oxidative stress. Since oxidative stress frequently results in DNA strand breakage, chromosomal abnormalities, and apoptosis, there are worries about its mutagenic and carcinogenic potentials (Teow et al., 2011). Additionally, it has been shown that exposure to ENMs causes immunological dysregulation and the generation of pro-inflammatory cytokines, both of which may contribute to the development of inflammatory disorders (Malakar et al., 2021).

3. Systemic Health Effects

ENMs exert toxic effects across multiple organ systems:

- Respiratory System: Inhalation of titanium dioxide, carbon-based nanomaterials, and metal oxide nanoparticles has been associated with lung inflammation, fibrosis, and impaired gas exchange (Warheit et al., 2008; Hristozov & Malsch, 2009). However, while Warheit et al. (2008) reported minimal acute toxicity in short-term inhalation studies involving TiO_2, Hristozov and Malsch (2009) observed significant chronic pulmonary responses under prolonged exposure. These contrasting findings underscore the importance of exposure duration, particle size, and surface chemistry in determining pulmonary outcomes.
- Cardiovascular System: Nanoparticles can also disrupt the homeostasis in the vascular system, increase thrombosis, and lead to endothelial dysfunction, and subsequently result in the development of cardiovascular diseases (Teow et al., 2011; Gajewicz et al., 2012).
- Neurological System: The study has indicated that certain ENMs can get past the blood-brain barrier and may lead to neuroinflammation, oxidative stress of the neurons, and possible connections to neurodegenerative disorders (Ma et al., 2024).
- Skin Problems: As cosmetic materials and personal care products consist of ENMs, such materials can permeate into the skin, leading to irritation, allergies, and even, in some cases, to cytotoxicity (Corsi et al., 2023).

4. Biomedical Applications and Safety Challenges

Even though engineered nanomaterials (ENMs) have proliferated in drug delivery systems, diagnostics, and theranostics, their bioactivity raises safety issues. As an example, metals such as silver and gold can form nanoparticles that eventually accumulate in organs, causing chronic toxicity. Although these materials are very functional, they have to pass through strict biocompatibility tests, such as long-term toxicity tests, before they can be used in the clinic (Malik et al., 2023; Ma et al., 2024).

IV. Environmental Impact of Engineered Nanomaterials

1. **Environmental Fate and Transport**: As almost all engineered nanomaterials (ENMs) are now being used on a widespread scale, they are even being accumulated throughout different environmental compartments, causing concerns about their long-term ecological effects. Despite the many benefits that ENMs provide, which include the use of pollution remediation, energy efficiency, and agricultural productivity, there is a need to investigate how they could have unintended consequences on the ecosystem, biodiversity, and the microbial community. ENMs are persistent, available, and have preferred mechanisms to transport through air, water, and soil, which control their environmental fate. Released ENMs can be accumulated by organisms at multiple trophic levels. This is especially worrying for metal-based nanoparticles such as silver (AgNPs) and titanium dioxide (TiO_2) that are found in aquatic organisms. Bioaccumulation of such substances is dangerous for biomagnification in food chains and, therefore, may affect human consumers as well (Corsi et al., 2023; Hristozov & Malsch, 2009). The persistence of ENMs is also highly variable depending on their composition and physicochemical properties. Grease and fabric-based nanomaterials, including graphene and carbon nanotubes (CNTs), have very low degradation resistance to the environment and can remain in the environment for a long time (Singh et al., 2024). On the other extreme, however,

biodegradable polymeric nanoparticles utilize enzymes existing in their surroundings to degrade, thus possibly alleviating their long-term footprint on the environment (Malakar et al., 2021).

2. **Ecotoxicity and Biodiversity Concerns**: ENMs are potentially ecotoxic and biodiversity threatening to aquatic and terrestrial life and microbial communities. Such risks are especially apparent in industrial effluents, agricultural runoffs, and effluents of wastewater effluents, where nanoparticles can build up and disrupt ecological balance. As explained in Section III, ENMs like silver and zinc oxide nanoparticles can cause oxidative stress that also makes them ecotoxic in aquatic and terrestrial environments. In combination with their bactericidal activity, this process can disrupt the microbiome, impair algal productivity, and the reproductive health of aquatic life (Corsi et al., 2023; Hristozov & Malsch, 2009). ENM in a terrestrial ecosystem behaves similarly in that they accumulate in the soils and eventually produce an impact on the growth and microbial activity in the soil. One of such groups of nanoparticles, which have been reported to suppress root growth and nutrient acquisition, is zinc oxide (ZnO) (Shukla et al., 2024). ENM also influences the physiological stress of soil invertebrates like earthworms, particularly when high concentrations have been involved (Corsi et al., 2023). Silver nanoparticles are known to inhibit microbial activity in wastewater treatment plants, potentially disrupting biogeochemical cycling. However, findings remain mixed. For instance, Corsi et al. (2023) observed strong antimicrobial effects that impaired microbial community structure and enzyme function in activated sludge. In contrast, Chen and Chen (2017) reported minimal disruption at environmentally relevant concentrations, suggesting that the extent of toxicity may depend on nanoparticle size, surface coatings, and environmental dilution factors. These inconsistencies highlight the need for standardized exposure models and real-world validation.
3. **Environmental Exposure Pathways**: ENMs enter the environment via several such pathways, industrial discharge, atmospheric deposition, and agricultural applications. Nanoparticles are released into water bodies as part of industrial processes that use nanotechnology and incorporate them into wastewater effluents. Although conventional wastewater treatment plants are not designed to capture or remove nanoparticles, many of these particles are getting into aquatic environments (Corsi et al., 2023). Apart from waterborne pathways, airborne nanoparticles from industrial emissions and combustion processes can also settle over land and water surfaces. Environmental contamination and inhalation risks to humans and animals (Warheit et al., 2008) result from these airborne particles. Another very high exposure route is that related to agriculture, where the number of nano fertilizers and nano pesticides increases. However, these nanomaterials can remain in soils and eventually leach into the surrounding water bodies, which can cause potential risks to non-target organisms and disrupt natural ecosystems (Shukla et al., 2024).

A structured approach to assessing the risks of engineered nanomaterials, from hazard identification to regulatory decision-making, is depicted in Figure 3

Figure 3: Risk assessment cycle

Identified Gaps and Controversies in Literature

Although the body of research on the toxicological and ecological impact of engineered nanomaterials (ENMs) is sufficiently extensive, the gaps and inconsistencies remain significant, which complicates the risk assessment and regulation of the matter. Inconsistent findings are usually made to do with dose-related toxicity, the effect of surface coatings, and biological response that is species-specific. An example is that whereas certain studies show that zinc oxide (ZnO) nanoparticles are phytotoxic at low concentrations due to foliar dissolution and plant tolerance (Lin & Xing, 2008), others have shown that root elongation inhibition and microbial activity can be severely inhibited at the same concentrations (Dimkpa et al., 2012).

Moreover, individual ENMs are studied in controlled laboratory conditions in most toxicological studies. This does not depict the realism of the environmental exposures, where various nanomaterials can interact either synergistically or antagonistically (Holden et al., 2014). Paucity of multi-pollutant investigations, in addition to the absence of chronic low-dose and field-based exposure information, restricts the externalization of laboratory results to the real world (Nel et al., 2006).

Lack of standardized testing procedures in the various laboratories is another major issue. Variation in the methods of production of nanoparticles, dispersion protocols, and exposure often leads to conflicting results, even between the same nanomaterial (Oberdörster et al., 2005). Such difficulties point to a necessity for standardized experimental designs and ecological monitoring in the long term. To go on, in the future, the integrated solutions approach should be used in the research that mimics environment matrices, uses consistent toxicological endpoints, and evaluates ENM over time.

V. Risk Assessment and Regulatory Framework

As ENMs have rapidly proliferated, there is a need for comprehensive risk assessment methodologies and regulatory measures for the security of ENMs concerning both human and environmental factors.

1. Current Approaches to Risk Assessment

- Hazard Identification and Dose-Response Relationships: The risk assessment of ENMs is based on the toxicity of ENMs at different exposure levels. Laboratory studies and computational models assess the relationship between nanoparticle concentration and adverse biological effects (Gajewicz et al., 2012).
- Exposure Assessment Methods: Detecting ENM exposure requires sophisticated technology such as electron microscopy, dynamic light scattering, and spectroscopy (Huang et al., 2024). Nevertheless, quantifying ENMs in complex environmental matrices is still challenging.

2. Challenges in Regulating ENMs

Although there is increasing recognition of the risks associated with ENM, there remain difficulties in the regulation of ENM since there are currently no standardized testing protocols available, and nanotoxicology studies remain difficult to perform.

- Lack of Standardized Testing Protocols: Conventional chemicals were currently designed for conventional toxicological assays, but not for nanoscale materials. According to Isibor et al. (2024), recent research has called for the need for nano-specific safety assessments.
- Complexity of Nanotoxicology Studies: The high diversity of ENMs in terms of size, composition, and surface properties poses a problem to the risk assessment. While traditional chemicals are assessed case by case, ENMs are toxic on a size-dependent basis (Gajewicz et al., 2012).

3. International Regulatory Frameworks

Various regulatory agencies have developed some guidelines to assess and manage ENM risks, which are shown in Table 2.

Table 2: Regulatory Frameworks for Engineered Nanomaterials (ENMs) Across Global Agencies

Regulatory Agency	Key Regulations and Guidelines	Reference
US Environmental Protection Agency (EPA)	Toxic Substances Control Act (TSCA) – Evaluates nanomaterial toxicity and environmental impact.	Corsi et al., 2023
European Chemicals Agency (ECHA)	Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) – Monitors ENMs in commercial products	Huang et al., 2024
World Health Organization (WHO)	Nanotechnology and Health Guidelines – Addresses occupational safety and public health concerns.	Ma et al., 2024
International Organization for Standardization (ISO)	Nanotechnology Standards (ISO/TC 229) – Develop protocols for nanomaterial characterization and risk assessment	Isibor et al., 2024

4. Ethical Considerations and Public Perception

- Concerns of Ethics in the Unrestricted Use of Nanotechnology: One ethical issue raised by nanotechnology is whether the use of nanotechnologies requires informed consent, constructs fairly upon the benefit of all population groups, and whether the inclusive effort generates unintended harm. However, it has been pointed out that the ENM adoption may be faster than the speed of risk assessment, which could result in risk to the health and environment of unknown damage (Hristozov & Malsch, 2009).
- Public Awareness and Risk Communication: Nanotechnology is perceived publicly in many different ways, ranging from uneasiness about safety and regulatory oversight to fascination with transparency between the company and researcher. Successful risk communication strategies are required to connect scientific advances with social acceptance (Gajewicz et al., 2012).

VI. Summary of Key Findings

This section offers a comparative summary of recent findings on the health and environmental impacts of the most significant engineered nanomaterials (ENMs) (Table 3). It aims to synthesize evidence on different types of ENMs to provide a clearer understanding of their dual nature and guide future research and regulatory efforts.

Table 3. Comparative Summary of Health and Environmental Effects of Common Engineered Nanomaterials

ENM Type	Health Effects	Environmental Effects	Key References	Evidence Consistency
Silver (Ag) NPs	ROS generation, inflammation, cytotoxicity	Microbial disruption in wastewater; bioaccumulation	Corsi et al., 2023; Chen & Chen, 2017	Moderate (varies by dose and coating)
Titanium Dioxide (TiO_2)	Lung inflammation, skin sensitivity, fibrosis	Persistent in soil/water; affects algae	Warheit et al., 2008; Huang et al., 2024	Contradictory (short-term vs. chronic effects)
Carbon Nanotubes (CNTs)	Neurotoxicity, oxidative stress	Long-term persistence, microbial imbalance	Singh et al., 2024; Hristozov & Malsch, 2009	High (consistent across studies)
Quantum Dots (QDs)	DNA damage, heavy metal leakage	Soil and water contamination risk	Ma et al., 2024; Gajewicz et al., 2012	Limited (due to fewer environmental studies)
Zinc Oxide (ZnO) NPs	ROS production, apoptosis	Inhibits plant growth; microbial shifts	Shukla et al., 2024; Ganguly et al., 2018	Inconsistent (species and media-dependent)
Polymeric NPs (e.g., PLGA)	Generally low toxicity	Biodegradable; minimal persistence	Malik et al., 2023; Malakar et al., 2021	High (reliable across biocompatibility tests)

Key Insights:

- Metal-based ENMs like silver and titanium dioxide are the most toxic and persistent to the environment.
- Carbon-based ENMs and quantum dots are dangerous because of their chemical stability and the possibility of emitting toxic components.
- Polymeric nanoparticles are safer, although they need more longitudinal studies to establish low-risk profiles.
- The most common environmental impacts are microbial imbalance, bioaccumulation, and effects on aquatic food chains.

VII. Strategies for Mitigation and Sustainable Development

Integration of engineered nanomaterials (ENMs) amongst industries has increased and thus needs to be mitigated in terms of their health and environmental risks. The sustainable nanotechnology approaches encourage the growth of environmentally responsive and decomposable agents and minimize exposure to the agents through design and monitoring technologies. This section then proceeds to emphasize key pathways for reducing nanomaterial-associated risk and facilitating sustainable development.

1. Green Nanotechnology Approaches

The emphasis of green nanotechnology is on the development of sustainable alternatives to ENMs, where the footprint on the environment of the nanomaterials is minimized concerning toxicological risks. It is based on the use of recyclable and decomposable nanomaterials and sustainable synthesis methods.

- Biodegradable and Eco-Friendly Nanomaterials: In recent years, green nanotechnology has advanced to the point at which biodegradable nanomaterials have been designed that degrade into non-toxic byproducts. Chitosan, polylactic acid (PLA), and poly (lactic-co-glycolic acid) (PLGA) based polymeric nanoparticles have shown biodegradability with functional efficacy in biomedical applications (Patni & Bhatia, 2008). Also, nanocellulose-based materials from plant sources are renewable alternatives to synthetic polymers for packaging and biomedical uses (Murphy, 2010).
- Sustainable Synthesis Methods: Nanomaterial synthesis based on sustainable principles includes green chemistry principles that minimize the use and generation of hazardous byproducts. The chemical reduction methods used for synthesizing metal nanoparticles have been an alternative route for green synthesis, such as plant extracts, microbial fermentation, and biopolymers (National Research Council, 2009). Secondly, solvent-free and energy-efficient fabrication techniques, for example, microwave-assisted synthesis and mechanochemical process, are developed to minimize the environmental impact (National Research Council, 2013).

2. Safe Design of Nanomaterials

The idea of safer by design revolves around designing nanomaterials that are as nontoxic as possible for their intended functions. Among the Key approaches for safer biomaterials are surface modifications, controlled release systems, and reduced bio-persistence.

- Modifications to Reduce Toxicity While Retaining Functionality: The interaction of ENMs with biological systems can be greatly affected by surface functionalization. For instance, coating nanoparticles with polyethylene glycol (PEGylation) improves immune recognition by lowering the inflammation response while barely impairing the drug delivery efficacy (Rajabzadeh, 2025). For instance, following the doping of metal nanoparticles with harmless substances (such as iron-doped titanium dioxide), the degree of oxidative stress and cytotoxicity has been decreased, while photocatalytic activity has been conserved (Brune et al. 2006).

- Safer-By-Design Strategies for ENMs: By degrading into biocompatible components after use, nanomaterials can be engineered to decrease the accumulation that would otherwise be present in the environment for such a long time. Enzyme-responsive and pH-sensitive nanoparticles are being researched to ensure controlled degradation under physiological and environmental conditions (Clunan & Rodine-Hardy, 2014). Moreover, hybrid nanomaterials comprising biodegradable and inert components are studied to balance safety and functionality (Corsi et al., 2023).

3. Advancements in Detection and Monitoring

Therefore, it is essential to monitor ENMs effectively in biological and environmental systems to do a risk assessment and comply with regulations. The tracking of nano pollution and its exposure assessment continuously improve through the use of emerging analytical techniques and early warning systems.

- Advanced characterization techniques: High-resolution transmission electron microscopy (HR-TEM), dynamic light scattering (DLS), and inductively coupled plasma mass spectrometry (ICP-MS) can provide accurate quantification of ENMs in complicated matrices (Sargent Jr., 2011). The second reason is that the application of nanotoxicology assays using in vitro organ-on-chip models in conjunction with high-throughput screening technologies facilitates rapid evaluation of interactions between ENMs and biological systems (Sequeira et al., 2006).
- Nanopollution Early Warning Systems: Real-Time Sensing Technologies enable Early Detection of Nanoparticles in Air and Water. On-site nanoparticle detection is being performed with surface-enhanced Raman spectroscopy (SERS) based nanosensors and fluorescent quantum dot probes (Zhuang & Gentry, 2011). Additionally, machine learning algorithms for predicting nanotoxicology help advance such tools as well as offer the potential to identify and avoid adverse outcomes sight unseen (Ma et al., 2024).

4. Future Perspectives in Nanotechnology Safety

Emerging trends and developing novel strategies to mitigate the risk of nanotechnology will influence the course of safety research into the future.

- Emerging Research on Minimizing Health and Environmental Risks: Long-term chronic exposure effects of ENMs are being studied in the future in occupational settings and consumer products (Hussain & Mishra, 2018). In silico models and computational toxicology approaches are ascending, which provide the means of faster prediction of ENM interactions with biological systems (Gajewicz et al., 2012). In addition, new nanomaterials are being screened for genotoxicity to assess their potential carcinogenicity (Carlin, 2014).
- Potential Breakthroughs in Nanotoxicology and Risk Mitigation: One of the critical milestones in nanotechnology safety, entails the fabrication of bio-inspired nanomaterials, which replicate the natural shape to make the material biocompatible and therefore reduce the toxicity (Tawiah et al., 2024). In addition, ways to remove toxic nanomaterials from water and soil using nanoparticle-based remediation techniques are also explored to minimize the risks of contamination (Malakar et al., 2021).

5. Limitations and Future Research Directions

Even though our knowledge of ENM toxicity and environmental persistence has been enhanced by many studies, there are still gaps in long-term epidemiological data, nano-bio interface interactions, and real-life exposure models. It can be hoped that future research in ENM will include engineering standardized, high-throughput screening assays, examining ENM fate in the complex matrices of the environment, and assessing chronic low-dose effects under realistic exposure conditions. Moreover, toxicologists, material scientists, and policymakers should work together to tackle these issues altogether.

VIII. Conclusion and Recommendations

Engineered nanomaterials (ENMs) hold the potential to revolutionize medicine, electronics, agriculture, and environmental cleanup. Their nanoscale features give them unique physicochemical properties that enhance their performance and functions. However, these same properties can also be very dangerous, leading to oxidative stress, cytotoxicity, and environmental persistence. The review highlights the dual nature of ENMs, offering innovation on one side and presenting health and ecosystem risks on the other. Recent studies indicate that some ENMs, particularly metal-based and carbon-derived types, can accumulate in biological systems and disrupt ecological balances, such as microbial communities and food webs. Current risk assessment models remain fragmented, with limited standardization and insufficient long-term exposure data.

To facilitate responsible innovation, the following recommendations are put forward, which are stakeholder-specific:
For Researchers:

- Give precedence to longitudinal in vivo and in vitro studies of chronic exposure.
- Derive and confirm predictive models with the help of computational toxicology and AI.

Research the ENM's interactions with certain biological systems (immune and neurological pathways).

For Regulators:

- Implement nano-specific guidelines and labeling requirements.
- Mandate standardized testing protocols across sectors and geographies.
- Support collaborative databases to track ENM toxicity data globally.

For Industry Stakeholders:

- Invest in safer-by-design nanomaterials, which are less toxic but still functional.
- Adopt green synthesis and biodegradable alternatives.
- Conduct thorough life-cycle assessments of ENM-enabled products.

Lastly, the future of nanotechnology should be accompanied by public awareness and open communication. The advantages of ENMs can only be achieved by cross-disciplinary cooperation, strong safety systems, and ethical integration to reduce the risks to human and environmental health.

References

1. Albrecht, M. A., Evans, C. W., & Raston, C. L. (2006). Green chemistry and the health implications of nanoparticles. *Green chemistry*, *8*(5), 417-432.
2. Brune, H., Ernst, H., Grunwald, A., Grünwald, W., Hofmann, H., Krug, H., ... & Wyrwa, D. (2006). *Nanotechnology: assessment and perspectives* (Vol. 27). Springer Science & Business Media.
3. Carlin, D. J. (2014). Nanotoxicology and nanotechnology: new findings from the NIEHS and Superfund Research Program scientific community. *Reviews on environmental health*, *29*(1-2), 105-107.
4. Chen, R., & Chen, C. (2017). Environment, health, and safety issues in nanotechnology. *Springer handbook of nanotechnology*, 1559-1586.
5. Clunan, A., & Rodine-Hardy, K. (2014). Nanotechnology in a globalized world: strategic assessments of an emerging technology.
6. Corsi, I., Venditti, I., Trotta, F., & Punta, C. (2023). Environmental safety of nanotechnologies: The eco-design of manufactured nanomaterials for environmental remediation. *Science of The Total Environment*, *864*, 161181.
7. Dimkpa, C. O., McLean, J. E., Martineau, N., Britt, D. W., Haverkamp, R., & Anderson, A. J. (2013). Silver nanoparticles disrupt wheat (Triticum aestivum L.) growth in a sand matrix. *Environmental science & technology*, *47*(2), 1082–1090. https://doi.org/10.1021/es302973y
8. Gajewicz, A., Rasulev, B., Dinadayalane, T. C., Urbaszek, P., Puzyn, T., Leszczynska, D., & Leszczynski, J. (2012). Advancing risk assessment of engineered nanomaterials: application of computational approaches. *Advanced drug delivery reviews*, *64*(15), 1663-1693.
9. Ganguly, P., Breen, A., & Pillai, S. C. (2018). Toxicity of nanomaterials: Exposure, pathways, assessment, and recent advances. *ACS Biomaterials Science & Engineering*, *4*(7), 2237-2275.
10. Holden, P. A., Klaessig, F., Turco, R. F., Priester, J. H., Rico, C. M., Avila-Arias, H., Mortimer, M., Pacpaco, K., & Gardea-Torresdey, J. L. (2014). Evaluation of exposure concentrations used in assessing manufactured nanomaterial environmental hazards: Are they relevant? *Environmental Science & Technology, 48*(18), 10541–10551. https://doi.org/10.1021/es502440s
11. Hristozov, D., & Malsch, I. (2009). Hazards and risks of engineered nanoparticles for the environment and human health. *Sustainability*, *1*(4), 1161-1194.
12. Huang, X., Auffan, M., Eckelman, M. J., Elimelech, M., Kim, J. H., Rose, J., ... & Alvarez, P. J. (2024). Trends, risks and opportunities in environmental nanotechnology. *Nature Reviews Earth & Environment*, *5*(8), 572-587.
13. Hussain, C. M., & Mishra, A. K. (2018). *Nanotechnology in environmental science, 2 volumes* (Vol. 1). John Wiley & Sons.
14. Isibor, P. O., Kayode-Edwards, I. I., Oyewole, O. A., Agbontaen, D. O., Onwaeze, O. O., Paul, E., ... & Chimbekujwo, K. I. (2024). Risk assessment and management in nanotoxicology. In *Environmental Nanotoxicology: Combatting the minute contaminants* (pp. 267-293). Cham: Springer Nature Switzerland.
15. Lin, D., & Xing, B. (2008). Root uptake and phytotoxicity of ZnO nanoparticles. *Environmental Science & Technology, 42*(15), 5580–5585. https://doi.org/10.1021/es800422x
16. Ma, X., Tian, Y., Yang, R., Wang, H., Allahou, L. W., Chang, J., ... & Poma, A. (2024). Nanotechnology in healthcare, and its safety and environmental risks. *Journal of nanobiotechnology*, *22*(1), 715.
17. Malakar, A., Kanel, S. R., Ray, C., Snow, D. D., & Nadagouda, M. N. (2021). Nanomaterials in the environment, human exposure pathway, and health effects: A review. *Science of the Total Environment*, *759*, 143470.
18. Malik, S., Muhammad, K., & Waheed, Y. (2023). Emerging applications of nanotechnology in healthcare and medicine. *Molecules*, *28*(18), 6624.
19. Murphy, P. (2010). *Nanotechnology: Public engagement with health, environment and social issues* (pp. 0-69). EPA.
20. National Research Council, Division on Engineering, Physical Sciences, Division on Earth, Life Studies, National Materials, ... & Safety Aspects of Engineered Nanomaterials. (2013). Research progress on environmental, health, and safety aspects of engineered nanomaterials.
21. National Research Council, Division on Engineering, Physical Sciences, National Materials Advisory Board, Division on Earth, Life Studies, ... & Safety Research Needs for Engineered Nanoscale Materials. (2009). Review of the federal strategy for nanotechnology-related environmental, health, and safety research.
22. Nel, A., Xia, T., Mädler, L., & Li, N. (2006). Toxic potential of materials at the nanolevel. *Science, 311*(5761), 622–627. https://doi.org/10.1126/science.1114397
23. Oberdörster, G., Oberdörster, E., & Oberdörster, J. (2005). Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles. *Environmental Health Perspectives, 113*(7), 823–839. https://doi.org/10.1289/ehp.7339
24. Patni, S., & Bhatia, A. L. (2008). Nanotechnology: A double edged sword. *Asian Journal of experimental sciences*, *22*(2), 153-66.

25. Rajabzadeh, H. (2025). Nanotechnology in Environmental Remediation: Opportunities and Risks. *International Journal of New Chemistry*, *12*(4), 774-791.
26. Nel, André & Grainger, David & Alvarez, Pedro & Badesha, Santokh & Castranova, Vincent & Ferrari, Mauro & Godwin, Hilary & Grodzinski, Piotr & Morris, Jeff & Savage, Nora & Scott, Norman & Wiesner, Mark & Roco, Mihail & Hersam, Mark & Mirkin, Chad. (1970). Nanotechnology Environmental, Health, and Safety Issues. 10.1007/978-94-007-1168-6_5.
27. Sargent Jr, J. F. (2011). Nanotechnology and environmental, health, and safety: Issues for consideration.
28. Sequeira, R., Genaidy, A., Shell, R., Karwowski, W., Weckman, G., & Salem, S. (2006). The nano enterprise: A survey of health and safety concerns, considerations, and proposed improvement strategies to reduce potential adverse effects. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *16*(4), 343-368.
29. Shukla, K., Mishra, V., Singh, J., Varshney, V., Verma, R., & Srivastava, S. (2024). Nanotechnology in sustainable agriculture: A double-edged sword. *Journal of the Science of Food and Agriculture*, *104*(10), 5675-5688.
30. Singh, N. B., Kumar, B., Usman, U. L., & Susan, M. A. B. H. (2024). Nano revolution: exploring the frontiers of nanomaterials in science, technology, and society. *Nano-Structures & Nano-Objects*, *39*, 101299.
31. Tawiah, B., Ofori, E. A., & George, S. C. (2024). Nanotechnology in societal development. In *Nanotechnology in Societal Development* (pp. 1-64). Singapore: Springer Nature Singapore.
32. Teow, Y., Asharani, P. V., Hande, M. P., & Valiyaveettil, S. (2011). Health impact and safety of engineered nanomaterials. *Chemical communications*, *47*(25), 7025-7038.
33. Wahab, A., Muhammad, M., Ullah, S., Abdi, G., Shah, G. M., Zaman, W., & Ayaz, A. (2024). Agriculture and environmental management through nanotechnology: Eco-friendly nanomaterial synthesis for soil-plant systems, food safety, and sustainability. *Science of the Total Environment*, 171862.
34. Warheit, D. B., Sayes, C. M., Reed, K. L., & Swain, K. A. (2008). Health effects related to nanoparticle exposures: environmental, health and safety considerations for assessing hazards and risks. *Pharmacology & therapeutics*, *120*(1), 35-42.
35. Zhuang, J., & Gentry, R. W. (2011). Environmental application and risks of nanotechnology: a balanced view. In *Biotechnology and nanotechnology risk assessment: minding and managing the potential threats around us* (pp. 41-67). American Chemical Society.