Advancing Bioremediation through Engineered Nanoparticles and Microbial Interactions.

Sarah Oluwaseun Julius[1], Jimoh Islam Ariremako[2], Olowolafe Moronkemi Oluwaseun[3], Muritala Ilyas Okikiola[4], Peter Obaloluwa Agboola[5], Auwal Shehu Ali [6], Ahmad Alaaya Mashood [7], Sunusi Abubakar Adamu [8]

University of Ibadan, Department of Microbiology[1]

University of Ilorin, Department of Microbiology[2]

University of Ibadan, Department of Botany[3]

University of Ibadan, Department of Petroleum Engineering[4]

University of Barcelona, Department of Chemistry[5]

Federal Teaching Hospital; Kastsina, Department of Pharmacy[6]

Kyungpook National University; South Korea, Department of Environmental Engineering[7]

Gombe state University, Department of Geography and Environmental Management[8]

DOI: https://doi.org/10.51244/IJRSI.2025.1210000137

Received: 07 October 2025; Accepted: 14 October 2025; Published: 08 November 2025

ABSTRACT

Environmental pollution arising from industrialization, agricultural intensification, and rapid urbanization remains a major ecological and public health concern. Persistent contaminants such as heavy metals, hydrocarbons, pesticides, plastics, and pharmaceutical residues accumulate in soil and water, disrupting ecosystems and threatening human well-being. Conventional remediation methods, including chemical treatments, incineration, and physical removal, often provide incomplete solutions due to high costs, partial pollutant removal, and the generation of secondary waste.

Bioremediation offers a more sustainable alternative by harnessing microbial metabolism to degrade or detoxify pollutants. However, its efficiency is often limited by low pollutant bioavailability, slow degradation rates, and microbial sensitivity to toxic environments. Advances in nanotechnology have introduced engineered nanoparticles (ENPs) that can overcome these barriers through synergistic interactions with microorganisms. ENPs enhance pollutant solubilization, facilitate electron transfer, and improve microbial tolerance under stress, resulting in more efficient and adaptable remediation systems.

This review synthesizes recent progress in nano–bio remediation, emphasizing applications in heavy metal detoxification, hydrocarbon degradation, wastewater treatment, and plastic biodegradation. It also critically examines nanoparticle toxicity, environmental persistence, cost implications, and regulatory uncertainties. Finally, the paper highlights future directions focused on biocompatible nanomaterials, engineered microbial strains, interdisciplinary collaboration, and circular economy integration to ensure the safe, scalable, and sustainable deployment of nano–bio remediation technologies.

Keywords: Bioremediation, Engineered nanoparticles, Microbial interactions, nano-biotechnology, pollutant degradation

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

INTRODUCTION

Pollution remains one of the most persistent environmental challenges of the 21st century, driven by industrialization, agricultural intensification, and rapid urbanization. These processes continually release contaminants into soils, water bodies, and sediments, where they accumulate and destabilize ecosystems (1, 2). Heavy metals such as cadmium, lead, and arsenic bioaccumulate in food chains, posing long-term threats to biodiversity and human health (3). Hydrocarbon contamination from petroleum spills disrupts aquatic systems (4), while plastics, particularly microplastics, have become pervasive in both terrestrial and marine environments, altering habitats and introducing chemical hazards (5, 6). Pesticides and pharmaceutical residues further compound these risks, intensifying toxic stress and undermining food and water safety (7). Collectively, these pollutants impose a multifaceted global burden on ecosystem integrity, human well-being, and sustainable development (8).

Conventional remediation methods—such as excavation, incineration, and chemical treatments—have been widely used but often fail to deliver sustainable outcomes. They are costly, energy-intensive, and frequently generate secondary waste without addressing complex contaminant mixtures (9, 10). In contrast, bioremediation leverages microbial metabolism to detoxify or degrade pollutants, providing an environmentally friendly and economically viable alternative (11). However, bioremediation efficiency remains limited by factors such as poor pollutant solubility, low microbial activity, and inhibition under toxic or nutrient-deficient conditions (12).

Nanotechnology offers innovative pathways to overcome these limitations. Engineered nanoparticles (ENPs), characterized by their high surface area, tunable reactivity, and catalytic potential, provide novel means for pollutant degradation and immobilization (13). For instance, zero-valent iron nanoparticles sequester heavy metals and chlorinated hydrocarbons (14), titanium dioxide nanoparticles drive photocatalytic oxidation of persistent organics (15), and carbon-based nanomaterials effectively adsorb pesticides, dyes, and hydrocarbons (16).

The emerging integration of ENPs with microbial systems represents a major advancement in sustainable remediation. Rather than functioning independently, nanoparticles and microbes can operate synergistically—ENPs enhance pollutant solubility, promote electron transfer, and reduce microbial stress, while microbes can stabilize or biosynthesize nanoparticles, lowering ecological risks and costs (17, 18). This synergy, however, requires careful evaluation. Concerns remain regarding nanoparticle toxicity, environmental persistence, and uncertain regulatory oversight (19). Furthermore, cost implications, scalability, and biosafety monitoring must be addressed to ensure long-term feasibility.

Thus, this paper critically examines the dual role of nanotechnology and microbiology in advancing next-generation bioremediation. It explores not only their mechanistic interactions but also the economic, environmental, and policy dimensions that determine real-world applicability. By emphasizing innovation balanced with precaution, the integration of ENPs and microbial systems is presented as a transformative yet responsible approach toward scalable, cost-effective, and sustainable environmental remediation.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

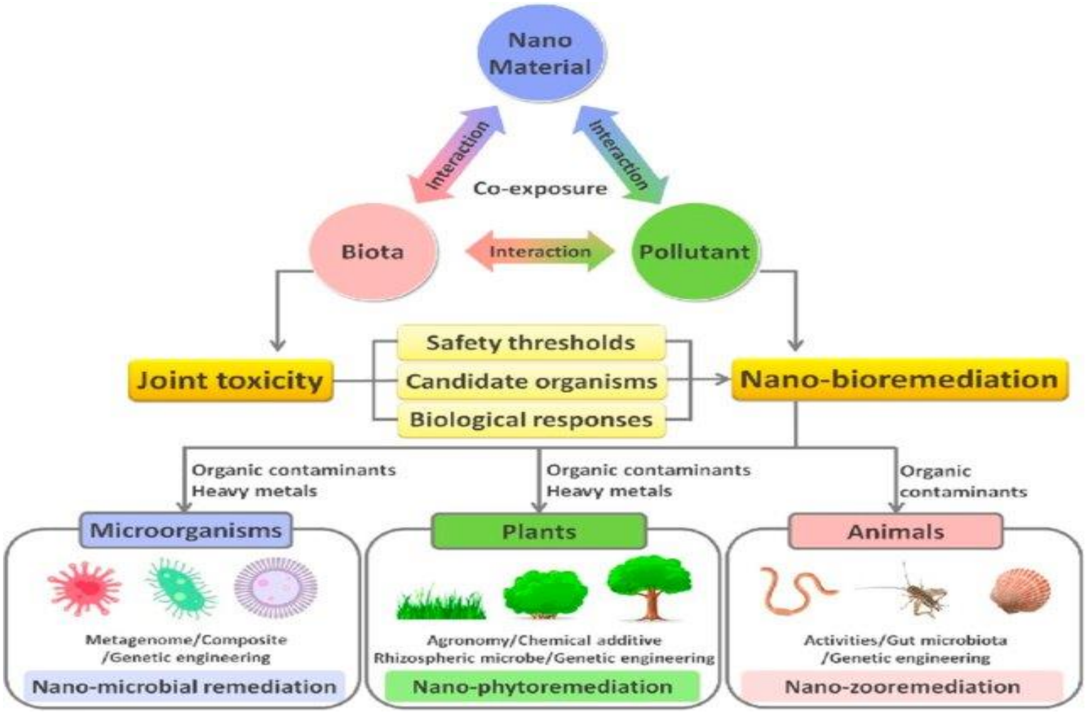

Figure 1: Schematic representation of interactions between engineered nanoparticles, microbial communities, and pollutants in environmental systems. This nano–bio synergy underpins sustainable bioremediation strategies. (20)

Table 1: Major Pollution Types and Limitations of Conventional Remediation

Pollutant Type	**Source**	**Conventional Remediation**	**Limitations**
Heavy metals	Industrial effluents, mining	Chemical precipitation, soil excavation	Expensive, partial removal, secondary waste
Hydrocarbons	Petroleum spills, industrial discharge	Bioremediation, chemical oxidation	Slow microbial degradation, low bioavailability
Plastics	Urban/industrial waste	Mechanical recycling	Limited efficiency, microplastics remain
Pesticides/ Pharmaceuticals	Agriculture, healthcare	Adsorption, chemical degradation	Incomplete breakdown, costly

2. Study Objectives

The overarching goal of this review is to deepen understanding of how engineered nanoparticles (ENPs) and microbial systems can be strategically integrated to enhance sustainable bioremediation. Specifically, the review aims to:

1. Synthesize current mechanisms and conceptual models governing ENP–microbe interactions, emphasizing how these partnerships improve pollutant solubility, facilitate redox reactions, and enhance microbial resilience under environmental stress.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

2. Assess major application domains where nano–bio remediation shows significant potential, including heavy metal detoxification, hydrocarbon degradation, plastic biodegradation, and wastewater treatment, with attention to both laboratory and emerging field-scale studies.

3. Critically evaluate technological, environmental, and socio-economic dimensions of nano–bio remediation. This includes addressing key barriers such as nanoparticle toxicity, environmental persistence, cost implications, and limited scalability, as well as policy gaps and regulatory uncertainties affecting industrial deployment.

4. Propose forward-looking frameworks that integrate biocompatible and cost-effective nanomaterials, engineered microbial consortia, and smart nano–bio hybrids. The review also considers how these systems can align with sustainability principles, circular economy objectives, and the United Nations Sustainable Development Goals (SDGs), while ensuring biosafety and responsible innovation.

METHODOLOGICAL APPROACH

Databases and Search Strategy

Relevant literature was systematically retrieved from major scientific databases, including Web of Science, Scopus, PubMed, and Google Scholar, chosen for their comprehensive coverage of environmental sciences, nanotechnology, and microbiology. Search strings combined targeted keywords such as “engineered nanoparticles,” “bioremediation,” “microbial interactions,” “nano–bio remediation,” “environmental pollution,” and “sustainability.” Boolean operators (AND, OR) were used to refine search results and ensure inclusiveness. The literature search covered publications from 2000 to 2024, capturing two decades of accelerated research and industrial application of nanotechnology in environmental remediation.

Inclusion Criteria

Studies were included if they:

- Were peer-reviewed and published in English.
- Provided direct insights into ENP–microbe interactions for environmental remediation.
- Presented conceptual models, mechanistic explanations, case studies, or techno-economic evaluations related to nano–bio remediation.
- Discussed sustainability or biosafety implications, aligning with the review’s interdisciplinary scope.

Priority was given to studies addressing real-world applications, scalability, and risk assessment, particularly those offering perspectives on biosafety, economic feasibility, or policy frameworks that support responsible adoption.

Exclusion Criteria

Publications were excluded if they focused on non-environmental uses of nanotechnology (e.g., clinical, pharmaceutical, or medical applications), gray literature, patents, or non-English sources. Studies concentrating solely on physicochemical remediation methods without microbial integration were also excluded, as the focus of this review is the synergistic relationship between ENPs and microorganisms.

Thematic Focus

The review adopted a thematic synthesis approach, structured around four analytical categories to ensure comprehensive coverage and critical depth:

1. Mechanistic insights: fundamental concepts of ENP–microbe interactions and their biocatalytic implications.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

2. Application domains: environmental sectors such as heavy metal detoxification, hydrocarbon degradation, plastic biodegradation, and wastewater treatment.
3. Critical synthesis: valuation of opportunities, risks, techno-economic feasibility, and policy readiness.
4. Future frameworks – pathways toward sustainable and circular nano–bio remediation through biocompatible materials, microbial engineering, and regulatory alignment.

This methodology enabled not only a synthesis of existing knowledge but also a critical appraisal of research gaps, cost implications, and policy dimensions necessary for translating nano–bio remediation from laboratory innovation to industrial implementation.

LITERATURE REVIEW

Engineered Nanoparticles as Catalysts for Bioremediation

Engineered nanoparticles (ENPs) have emerged as powerful catalytic agents that enhance microbial bioremediation by improving pollutant bioavailability, facilitating redox reactions, and stimulating microbial enzyme activity. Their nanoscale dimensions and high surface reactivity help address persistent limitations of conventional bioremediation, including poor pollutant solubility, limited microbial access, and slow degradation rates (21, 22).

ENPs are broadly classified into metal-based, carbon-based, polymeric, and magnetic types, each offering distinct catalytic and functional advantages in pollutant remediation (23). Among these, metal-based and carbon-based nanoparticles have demonstrated the greatest efficacy in laboratory and pilot-scale applications. Zero-valent iron nanoparticles (nZVI), for instance, immobilize heavy metals and catalyze dechlorination of chlorinated hydrocarbons while stimulating microbial dehydrogenase activity, thereby accelerating hydrocarbon degradation (14, 24). Carbon nanomaterials, including graphene oxide and carbon nanotubes, serve as efficient adsorbents for pesticides and hydrocarbons, reducing toxicity while promoting microbial biofilm formation and intercellular communication, both critical for sustained biodegradation (16, 25).

Polymeric and magnetic nanoparticles offer additional functional diversity. Polymeric nanoparticles are valued for their biocompatibility and tunable release properties, allowing them to deliver nutrients, cofactors, or enzymes that sustain microbial activity under stress conditions (23, 26). Magnetic nanoparticles, particularly iron oxides, not only adsorb pollutants but also allow for magnetic separation and reuse, improving process recovery and minimizing secondary contamination during wastewater treatment (27, 28).

However, the translation of ENP-assisted bioremediation from laboratory experiments to industrial or field applications remains constrained by cost, environmental persistence, and safety uncertainties. The synthesis of high-purity nanoparticles can be energy-intensive and expensive, which limits scalability in low-resource settings. Moreover, nanoparticle toxicity, arising from oxidative stress, ion release, or unintended interactions with non-target microbes, poses risks to ecological and human health (21, 29). Addressing these challenges requires risk assessment frameworks, biocompatible material design, and regulatory oversight that ensure safe deployment within circular and sustainable bioeconomy models.

In summary, ENPs function as catalytic partners to microbial systems, enhancing pollutant degradation through increased solubility, enzyme activation, and redox facilitation. Yet, realizing their full potential will depend on integrating biosafety measures, techno-economic optimization, and policy-driven governance to ensure that nano–bio remediation technologies are both effective and environmentally responsible at scale (Figure 2).

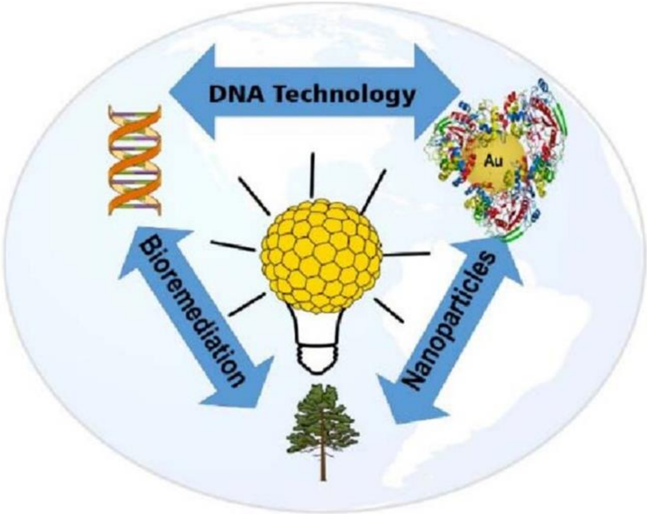

Figure 2. Conceptual representation of the integration of DNA technology, bioremediation, and engineered nanoparticles. (30)

Table 2: Engineered Nanoparticles as Catalysts for Bioremediation

ENP Type	Examples	Target Pollutants	Microbial Interaction/Enhancement	Mechanism
Metal-based	Zero-valent iron (nZVI), iron oxides, titanium dioxide (TiO_2)	Heavy metals (Cr, Pb, As), chlorinated hydrocarbons	Enhance microbial reduction, stabilize microbial consortia	Electron donation, pollutant immobilization, photocatalytic degradation
Carbon-based	Graphene oxide, carbon nanotubes, fullerenes	Hydrocarbons, PAHs, dyes	Stimulate microbial catabolic enzymes, promote biofilm formation	Adsorption, electron shuttle, pollutant solubilization
Polymeric	Chitosan, polymeric nanogels	Dyes, antibiotics, pharmaceutical residues	Deliver nutrients or enzymes to microbes, support microbial consortia	Enzyme stabilization, sustained release, pollutant adsorption
Magnetic	Iron oxide, cobalt ferrite nanoparticles	Heavy metals, dyes, organic pollutants	Facilitate microbial access, allow easy recovery of NPs	Adsorption, pollutant immobilization, magnetic separation

Microbial Adaptation and Interaction with Nanoparticles

Microorganisms exhibit remarkable adaptability to engineered nanoparticles (ENPs), often transforming potential stressors into opportunities for enhanced metabolism and pollutant degradation. While excessive ENP concentrations can induce oxidative stress and cellular damage, many microbes counteract these effects through antioxidant enzyme production, membrane restructuring, and activation of stress-response pathways (22, 29). These adaptive mechanisms not only mitigate toxicity but also enable microbes to use ENPs as electron donors or acceptors, thereby accelerating redox reactions that drive heavy metal detoxification and organic pollutant degradation (17).

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

A central adaptation mechanism involves biofilm formation, where ENPs enhance microbial adhesion and aggregation, reinforcing biofilm structure and stability (25). Biofilms create microenvironments that concentrate enzymes, protect cells from toxic exposure, and facilitate sustained pollutant breakdown. ENPs also stimulate the expression of **oxidoreductases,** hydrolases, and dehydrogenases**,** which catalyze the degradation of hydrocarbons, dyes, and pesticides (23). Furthermore, ENPs can act as redox mediators, promoting efficient electron transfer during microbial respiration and pollutant oxidation (28), thereby improving metabolic efficiency in contaminated environments.

Beyond adaptation, microbes can serve as bio-nanofactories, synthesizing and stabilizing nanoparticles through enzymatic reduction and biomineralization processes. Bacteria, fungi, and algae produce biogenic nanoparticles such as silver, zinc oxide, and iron oxides that are often more biocompatible and catalytically stable than their chemically synthesized counterparts (26, 27). Microbial exopolysaccharides and extracellular polymeric substances (EPS) further stabilize ENPs in situ, maintaining their dispersion, reducing aggregation, and prolonging catalytic activity (21). This dual functionality, tolerating ENPs while generating eco-friendly nanomaterials**,** positions microbes as both users and producers in advancing nano-enabled bioremediation systems (Figure 3).

However, these interactions are not without challenges. Persistent exposure to ENPs may lead to genetic mutations, altered microbial community dynamics, and potential ecological imbalances. Additionally, variability in nanoparticle type, size, and surface chemistry influences microbial responses, making biosafety evaluation and standardization essential for environmental deployment. The sustainability of such systems also depends on the economic feasibility of nanoparticle synthesis and the regulatory oversight governing their environmental use. Collaborative efforts among microbiologists, materials scientists, and policymakers are therefore critical to ensuring responsible innovation that balances technological advancement with environmental protection.

In summary, microbial adaptation to ENPs demonstrates significant potential for improving bioremediation efficiency, but responsible scaling requires integrating biosafety frameworks**,** long-term monitoring, and risk mitigation strategies alongside ongoing technological refinement.

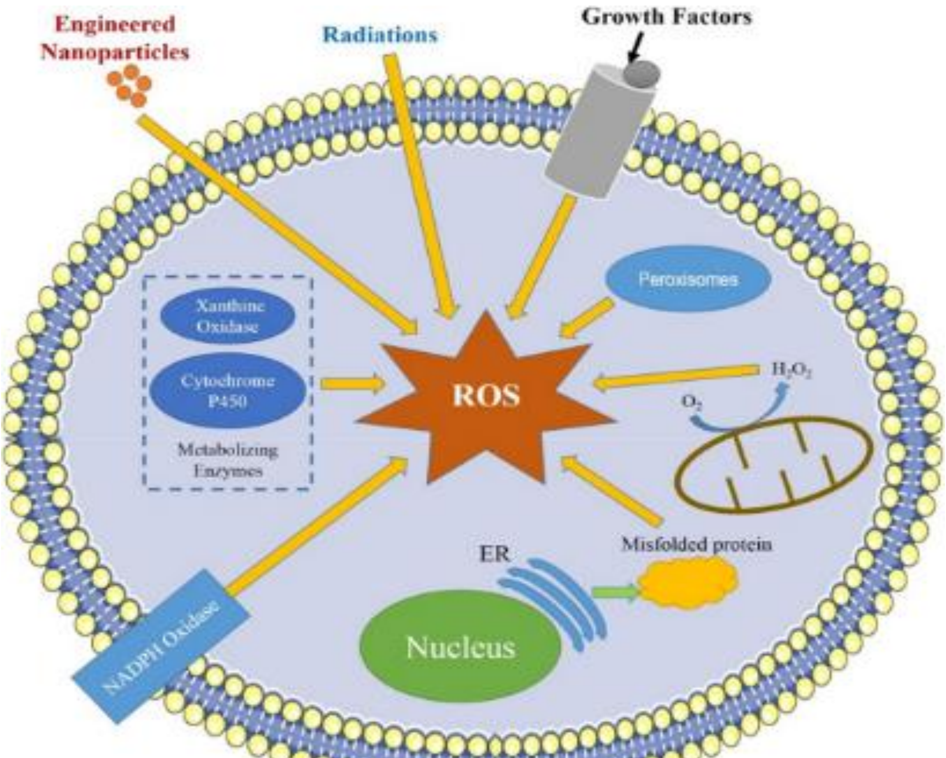

Figure 3: Mechanisms of reactive oxygen species (ROS) generation and microbial responses to engineered nanoparticles (ENPs). (31)

Table 3: Microbial Adaptation and Interaction with Engineered Nanoparticles

Microbial Adaptation	Example Mechanism	ENP Interaction	Outcome / Functional Role
Tolerance to ENPs	Efflux pumps, antioxidant enzymes, stress-response proteins	Metal-based NPs (nZVI, TiO_2)	Survive toxic nanoparticle environments, maintain metabolic activity
Biofilm Formation	EPS secretion, cell aggregation	Carbon-based NPs, magnetic NPs	Stabilizes microbes, enhances pollutant adsorption and degradation
Enzyme Induction	Upregulation of hydrolases, oxygenases, peroxidases	Graphene oxide, CNTs	Accelerates degradation of hydrocarbons, plastics, or dyes
Redox Mediation / Electron Transfer	Use of NPs as electron shuttles	Iron oxide, nZVI	Enhances redox reactions during pollutant breakdown
Biosynthesis / Stabilization of NPs	Microbes produce nanoparticles via biomineralization	Gold, silver, iron oxide	Reduces ecological risks, creates "green" nanoparticles for remediation

Application Domains as Case Frameworks

The integration of engineered nanoparticles (ENPs) with microbial systems spans several major pollution categories, revealing how nano–bio synergies can enhance environmental remediation. By improving pollutant bioavailability, facilitating enzymatic activity, and stabilizing microbial communities, ENPs extend the effectiveness of bioremediation beyond laboratory conditions. However, translating these advances into field-scale operations requires attention to cost, environmental risk, and regulatory feasibility. The following domains illustrate both the potential and practical considerations of these systems.

1. Heavy Metal Detoxification

Heavy metals such as chromium (Cr), lead (Pb), and arsenic (As) persist in soils, sediments, and water bodies, posing long-term ecological and public health threats (8, 32). Conventional treatments like chemical precipitation and soil excavation are costly, energy-intensive, and often incomplete. Nano–bio remediation offers a more sustainable and cost-effective alternative.

Zero-valent iron (nZVI) and iron oxide nanoparticles act as electron donors, immobilizing metals and transforming toxic ions into less harmful forms, thereby enhancing microbial detoxification through enzymatic reduction, methylation, and biosorption (14, 17, 22). ENPs also increase metal bioavailability, improving microbial access and accelerating detoxification kinetics (29).

Nevertheless, potential risks of metal nanoparticle toxicity and accumulation in the environment require long-term monitoring and standardized safety protocols. Developing biocompatible nanomaterials and promoting regional pilot-scale testing in Asia and Africa could improve adoption while reducing cost barriers (33, 34).

Hydrocarbon Degradation

Hydrocarbon pollution, especially from petroleum spills and polycyclic aromatic hydrocarbons (PAHs), presents major challenges due to their hydrophobicity and slow natural degradation rates (35). Carbon-based ENPs such

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

as graphene oxide, carbon nanotubes, and fullerenes adsorb hydrocarbons, mitigate toxicity, and promote microbial colonization and biofilm formation (16, 35). Through interactions with microbial consortia, ENPs upregulate catabolic enzymes like oxygenases and peroxidases, accelerating oxidation under both aerobic and anaerobic conditions (23, 24).

They also act as electron shuttles, facilitating redox reactions that enhance the degradation of recalcitrant PAHs (36). However, large-scale deployment remains constrained by nanomaterial production costs, recycling limitations, and potential ecotoxicity. Integrating low-cost, biosynthesized nanoparticles with indigenous microbial strains could improve feasibility for marine and terrestrial clean-up in developing regions.

Plastic Pollution

Plastic and microplastic pollution, particularly from polyethylene (PE) and polyethylene terephthalate (PET), has become a persistent global concern (5). ENPs can enhance enzymatic plastic degradation by stabilizing microbial hydrolases, increasing polymer contact, and promoting biofilm growth on plastic surfaces (26, 37).

This approach improves polymer breakdown rates and supports circular economy goals by converting waste plastics into value-added products. Yet, regulatory gaps, unknown by-products, and potential nanotoxic residues demand cautious scaling. Combining ENPs with genetically engineered microbes capable of expressing optimized plastic-degrading enzymes could accelerate progress while maintaining biosafety.

Wastewater Treatment

Industrial and municipal wastewater contains complex mixtures of dyes, antibiotics, and pharmaceuticals that often resist conventional treatment (21). Magnetic nanoparticles, such as iron oxide ENPs, enable adsorption and magnetic recovery, minimizing secondary pollution (27, 28). Polymeric nanoparticles can deliver nutrients or enzymes to sustain microbial consortia, while photocatalytic nanomaterials such as titanium dioxide (TiO_2) degrade organic pollutants under sunlight (15, 21).

These nano–bio systems enable simultaneous adsorption, degradation, and microbial stabilization, providing a multifunctional and scalable wastewater treatment model. Still, cost optimization, regulatory approval, and waste management of spent nanomaterials remain key bottlenecks. Future research should assess long-term environmental monitoring frameworks and cost–benefit models to guide responsible industrial adoption

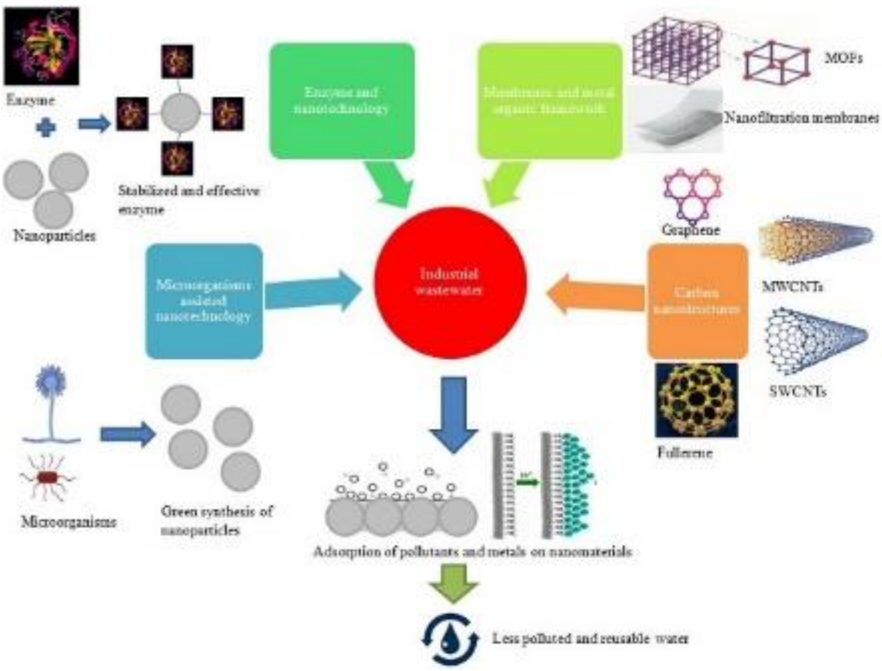

Figure 4: Utilization of various nanotechnology approaches in combination with microbial assistance for wastewater bioremediation. (38)

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

Table 4: Summary of ENPs and Microbial Roles Across Pollutant Domains

Pollutant Domain	**Specific Pollutants**	**Engineered Nanoparticles (ENPs)**	**Microbial Role**	**Key Mechanism/Outcome**
Heavy Metals	Cr, Pb, As	Zero-valent iron, iron oxides	Reduction, methylation, sequestration	ENPs increase bioavailability, accelerate detoxification
Hydrocarbons	Petroleum, PAHs	Graphene oxide, CNTs	Catabolic enzyme induction	ENPs adsorb hydrocarbons, act as electron shuttles
Plastics	PE, PET	Metal oxides, TiO_2	Hydrolase stabilization, biofilm formation	ENPs enhance enzymatic breakdown
Wastewater	Dyes, antibiotics, pharmaceuticals	Magnetic nanoparticles, polymeric ENPs, TiO_2	Enzyme delivery, microbial stabilization	Adsorption + photocatalytic degradation

Critical Insights and Analysis

The integration of engineered nanoparticles (ENPs) with microbial systems presents transformative opportunities for advancing bioremediation, offering faster degradation rates and broader pollutant coverage than conventional methods. ENPs enhance pollutant bioavailability, accelerate electron transfer, and stimulate microbial enzyme activity, enabling microbes to degrade contaminants more efficiently (39, 40). These synergies extend remediation capacity to diverse pollutants, including heavy metals, hydrocarbons, plastics, and pharmaceuticals, creating a versatile and scalable platform (41, 42). Moreover, ENP–microbe systems enable *in situ* applications, reducing the need for soil excavation or wastewater transport—an important advantage for sustainable and cost-effective remediation, especially in developing regions (21).

However, these benefits are accompanied by notable risks and uncertainties. Nanoparticles can exert toxic effects on beneficial microbes, disrupt ecological networks, or bioaccumulate in food chains, potentially causing secondary environmental hazards (43, 44). Their persistence and poorly understood transformations in natural systems pose additional challenges for long-term monitoring (45). These factors highlight the importance of biosafety assessment, lifecycle monitoring, and the use of biocompatible nanomaterials to minimize ecological risks while maintaining efficiency.

Critical gaps also persist in terms of scalability, regulation, and cost. Most evidence for ENP–microbe interactions remains limited to laboratory conditions, with few pilot or field-scale demonstrations where environmental complexity can alter outcomes (46, 47). The high cost of nanoparticle synthesis and lack of standardized production protocols further hinder industrial adoption, particularly in low-income regions burdened by pollution (8). In addition, regulatory uncertainty and fragmented international policies limit the safe and equitable deployment of nano–bio technologies (48). Therefore, effective advancement will depend on multidisciplinary collaboration, integrating material science, microbiology, environmental policy, and socio-economic analysis to ensure both innovation and accountability.

Future Frameworks for Nano–Bio Remediation

The future of nano–bio remediation lies in harmonizing innovation with sustainability, safety, and socio-economic inclusiveness. Although laboratory research demonstrates that ENPs can improve pollutant

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

degradation and microbial resilience, real-world translation requires integrating ecological safety, cost optimization, and policy alignment (49, 50). Embedding these technologies within frameworks such as the UN Sustainable Development Goals (SDGs) and the circular economy ensures that remediation contributes not only to cleaner environments but also to long-term resilience and equity (51, 52). The following sub-frameworks highlight critical directions for the field:

Biocompatible Nanoparticles

Designing environmentally benign nanomaterials is essential for risk mitigation. Green synthesis approaches using plant extracts, microbial routes, or natural polymers produce nanoparticles with reduced toxicity and improved degradability (42). Biodegradable coatings, such as chitosan, alginate, or polyethylene glycol, can enhance stability while minimizing harm to non-target species. Future research should emphasize cost-effective green production and lifecycle assessment to ensure environmental and economic sustainability.

Microbial Engineering

Advances in genetic and metabolic engineering allow the creation of microbial strains optimized for nano–bio remediation. Engineered microbes can be tailored to tolerate nanoparticle-induced stress, secrete synergistic enzymes, and maintain activity under adverse environmental conditions (50). These innovations bridge the gap between laboratory potential and industrial application, particularly when combined with adaptive bioprocess models that account for cost and ecological safety.

Nano–Bio Hybrids and Smart Nanomaterials

Emerging work on nano–bio hybrids merges microbial metabolism with nanocatalytic properties, enabling enhanced electron transfer and targeted pollutant degradation (53). Smart nanomaterials capable of pollutant-specific binding and controlled release offer precision and efficiency in remediation. For example, functionalized ENPs could selectively degrade pharmaceuticals or pesticides while minimizing off-target effects (49). Such systems, however, require rigorous risk–benefit analysis and transparent regulatory evaluation.

Sustainability and Systems Integration

Long-term impact depends on embedding nano–bio remediation within sustainability and systems frameworks. Alignment with SDGs such as clean water (Goal 6) and responsible consumption (Goal 12) promotes measurable global progress (51). Integrating circular economy principles enables recovery of resources from waste streams, closing the loop between remediation and production (52). A systems-based model; ENP design → microbial compatibility → pollutant degradation → sustainability assessment ensures iterative improvement that balances performance, cost, and environmental safety.

Policy, Safety, and Ethical Dimensions

Deploying ENPs for environmental remediation demands a balanced approach between technological innovation and ecological responsibility. Although ENP–microbe systems hold great potential for removing persistent pollutants, uncontrolled nanoparticle release could result in bioaccumulation, toxicity to non-target organisms, and microbial community disruption (41, 54, 55). Laboratory findings have shown that silver and titanium dioxide nanoparticles can inhibit microbial diversity and interfere with nutrient cycles, reinforcing the need for precautionary regulation and continuous environmental monitoring (56, 57).

Globally, regulatory frameworks remain fragmented, with few nations addressing deliberate ENP use in environmental settings (58, 59). This regulatory vacuum can exacerbate inequalities in monitoring and enforcement, particularly in low-resource regions (60). Developing harmonized international policies and science-based risk assessment standards is therefore essential to ensure safe and equitable deployment.

From an ethical standpoint, innovation must align with principles of environmental justice. Populations most affected by pollution often lack representation in decision-making around new remediation technologies (61, 62). Transparent communication, stakeholder inclusion, and public–private collaboration are vital for ensuring

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

fair distribution of benefits and accountability. A cross-sectoral approach involving scientists, regulators, and local communities will be key to ensuring that nano–bio remediation advances responsibly and equitably (50, 63).

Synthesis of Findings

Recent studies underscore the growing potential of ENPs in enhancing microbial bioremediation. Aliyari Rad *et al*. (2023) (64) demonstrated that nano–microbial remediation provides scalable, cost-effective pollutant removal through catalytic and biological synergy. Yang and Shen (2025) (65) highlighted the complexity of nanoparticle–microbe interactions in heavy metal detoxification, emphasizing the need for mechanistic understanding to optimize field performance.

Ayilara *et al.* (2023) (66) reinforced the importance of microbial adaptability and enzyme-mediated processes, aligning with findings by Yang and Shen (2025) (65) that call for context-specific microbial selection. Similarly, Unimke *et al.* (2024) (67) examined microbe–plant–nanoparticle interactions, illustrating how ENPs can accelerate petroleum hydrocarbon remediation while raising biosafety concerns.

Collectively, these findings affirm the promise of nano–bio remediation but also stress the necessity of comprehensive field validation, cost analysis, and biosafety assessment. Advancing the field will depend on balancing innovation with precaution, ensuring that nano–bio technologies are scalable, safe, and socially responsible.

CONCLUSION

Engineered nanoparticles (ENPs) offer transformative potential in microbial bioremediation by enhancing pollutant bioavailability, facilitating electron transfer, and stimulating enzymatic degradation. Their performance, however, depends on several interacting factors including nanoparticle type, concentration, microbial strain, and environmental conditions which must be optimized for consistent outcomes. While ENP microbe systems have demonstrated superior pollutant removal under laboratory settings, large-scale application remains constrained by issues of cost, biosafety, and uncertain long-term environmental behavior.

A critical balance between technological efficiency and ecological safety is therefore essential. Future research should prioritize mechanistic elucidation of nano–microbe interactions, cost-effective green synthesis, and the development of biocompatible nanomaterials that minimize toxicity and persistence. Field-scale trials, coupled with life-cycle and risk assessments, are vital to validate laboratory findings. Moreover, policy frameworks and interdisciplinary collaborations among microbiologists, material scientists, and environmental regulators will be crucial to guide responsible deployment. In summary, ENP-assisted microbial bioremediation represents a promising yet complex frontier for sustainable pollutant removal. Its long-term success will depend not only on scientific innovation but also on ensuring that environmental protection, economic feasibility, and public safety remain at the core of its advancement.

REFERENCES

1. United Nations Environment Programme (UNEP). Global Environment Outlook 6: Healthy Planet, Healthy People. Nairobi: UNEP; 2019.
2. Zhang Q, Xu EG, Li J, Chen Q, Ma L, Zeng EY, et al. A review of microplastics in table salt, drinking water, and air: Direct human exposure. Environ Sci Technol. 2020;54(7):3740–51.
3. Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN. Toxicity, mechanism and health effects of some heavy metals. Interdiscip Toxicol. 2014;7(2):60–72.
4. Varjani SJ. Microbial degradation of petroleum hydrocarbons. Bioresour Technol. 2017;223:277–86.
5. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv. 2017;3(7):e1700782.
6. Wright SL, Kelly FJ. Plastic and human health: A micro issue? Environ Sci Technol. 2017;51(12):6634–47.
7. Kümmerer K. The presence of pharmaceuticals in the environment due to human use – present knowledge and future challenges. J Environ Manage. 2009;90(8):2354–66.

8. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, Basu N, et al. The Lancet Commission on pollution and health. Lancet. 2018;391(10119):462–512.
9. Reddy KR, Cameselle C. Electrochemical Remediation Technologies for Polluted Soils, Sediments and Groundwater. Hoboken: Wiley; 2009.
10. Vidali M. Bioremediation. An overview. Pure Appl Chem. 2001;73(7):1163–72.
11. Megharaj M, Ramakrishnan B, Venkateswarlu K, Sethunathan N, Naidu R. Bioremediation approaches for organic pollutants: A critical perspective. Environ Int. 2011;37(8):1362–75.
12. Azubuike CC, Chikere CB, Okpokwasili GC. Bioremediation techniques – classification based on site of application: Principles, advantages, limitations and prospects. World J Microbiol Biotechnol. 2016;32(11):180.
13. Keller AA, Wang H, Zhou D, Lenihan HS, Cherr G, Cardinale BJ, et al. Stability and aggregation of metal oxide nanoparticles in natural aqueous matrices. Environ Sci Technol. 2013;44(6):1962–7.
14. Crane RA, Scott TB. Nanoscale zero-valent iron: Future prospects for an emerging water treatment technology. J Hazard Mater. 2012;211–212:112–25.
15. Fujishima A, Rao TN, Tryk DA. Titanium dioxide photocatalysis. J Photochem Photobiol C Photochem Rev. 2000;1(1):1–21.
16. Mauter MS, Elimelech M. Environmental applications of carbon-based nanomaterials. Environ Sci Technol. 2008;42(16):5843–59.
17. Rajput V, Minkina T, Sushkova S, Behal A, Maksimov A, Blicharska E, et al. ZnO and CuO nanoparticles: a threat to soil organisms, plants, and human health. Environ Geochem Health. 2020;42(1):147–58.
18. Singh J, Dutta T, Kim KH, Rawat M, Samddar P, Kumar P. ‘Green’ synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. J Nanobiotechnol. 2021;19:1–24.
19. Nowack B, Ranville JF, Crane M, Handy R, Baun A, Brouwer D, et al. Potential scenarios for nanomaterial release and subsequent alteration in the environment. Environ Toxicol Chem. 2012;31(1):50–9.
20. Jie Y, He M, Liu B, Jiang H. Interactions between engineered nanomaterials and microorganisms: Mechanisms, environmental impacts and applications. Ecotoxicol Environ Saf. 2019;169:483–95.
21. Adeleye AS, Conway JR, Garner K, Huang Y, Su Y, Keller AA. Engineered nanomaterials for water treatment and remediation: Costs, benefits, and applicability. Chem Eng J. 2016;286:640–62.
22. Kumar N, Shah V, Walker VK. Perturbation of an Arctic soil microbial community by metal oxide nanoparticles. Environ Toxicol Chem. 2019;38(3):525–32.
23. Sharma M, Sharma N, Jeon J, Lee S, Seo J. Nanoparticle-based emerging strategies for bioremediation of polluted environments: Applications and future perspectives. Environ Eng Res. 2020;25(6):847–61.
24. Wang W, Zhou W, Jiang Q, Zhang Y, Xu J. Enhanced bioremediation of petroleum hydrocarbons by nano zero-valent iron coupled with microbial consortium. J Hazard Mater. 2019;373:7–16.
25. Li Y, Gao Y, Zhang X, Yan X, Zhao H, Li X, et al. Graphene oxide-based nanomaterials for efficient removal of organic pollutants from wastewater. Chemosphere. 2020;246:125575.
26. Singh R, Shukla A, Yadav RS, Sharma PK. Polymeric nanoparticles in environmental remediation: A review on applications and perspectives. Environ Nanotechnol Monit Manag. 2022; 18:100704.
27. Hussain CM, Panwar J, Lee J, Sillanpää M. Magnetic nanoparticles: A sustainable platform for environmental remediation. J Environ Chem Eng. 2017;5(4):3606–13.
28. Zhou D, He B, Yang J, Hu X, Song W, Wang Y, et al. Application of magnetic nanoparticles for wastewater treatment: A review. Sci Total Environ. 2018;642:1028–39.
29. Das P, Barua S, Sarkar S, Chatterjee S, Mukherjee A. Nanoparticle toxicity in microorganisms: Mechanisms, impact and applications. Environ Nanotechnol Monit Manag. 2021;16:100502.
30. Vázquez-Núñez E, Molina-Guerrero CE, Peña-Castro JM, Fernández-Luqueño F, de la Rosa-Álvarez MG. Use of nanotechnology for the bioremediation of contaminants: a review. Processes. 2020;8(7):826.
31. Jaspreet K, Balpreet K, Amandeep S, Navneet K, Harmandeep S. Reactive oxygen species generation and microbial adaptations in response to engineered nanomaterials: mechanisms and implications. J Appl Microbiol. 2019;127(4):950–65.
32. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. Heavy metal toxicity and the environment. EXS. 2012;101:133–64.
33. Ghorbani M, Karimi B, Karimi H. Application of nano zero-valent iron and microbial consortia for remediation of heavy metal contaminated soil. Chemosphere. 2021;263:127973.

34. Li J, Huang Y, Li Y, Xu Y, Wang X, Zhang H. Synergistic remediation of arsenic and cadmium contaminated soils using iron oxide nanoparticles and indigenous microorganisms. J Hazard Mater. 2022;423:127115.
35. Das N, Chandran P. Microbial degradation of petroleum hydrocarbon contaminants: An overview. Biotechnol Res Int. 2011;2011:941810.
36. Ghosh P, Rathour R, Kar D, Singh RS, Chandra R. Synergistic effect of engineered nanoparticles and microbial consortia for enhanced degradation of polycyclic aromatic hydrocarbons. Environ Technol Innov. 2021;24:101908.
37. Zhang C, Chen X, Li C, Huang J, Yang W, Zhang W, et al. Nanoparticle-assisted enzymatic biodegradation of polyethylene terephthalate and polyethylene. Environ Sci Technol. 2021;55 (5):3074–85.
38. Mandeep, Shukla P. Microbial Nanotechnology for Bioremediation of Industrial Wastewater. Frontiers in Microbiology. 2020 Nov 2;11:590631.
39. Kumar R, Barati B, Mohanraj S, Saptoro A, Khanal SK. Engineered nanoparticles for environmental bioremediation: Mechanisms and applications. Environ Nanotechnol Monit Manag. 2019;12:100273.
40. Wang Z, Zhang T, Li J, Yu Y, Chen H, Sun Y, et al. Engineered nanoparticles for microbial-assisted pollutant degradation: Advances and perspectives. J Hazard Mater. 2019;374:1–13.
41. Rajput V, Minkina T, Sushkova S, Behal A, Singh R, Gorovtsov A, et al. Effects of nanoparticles on crops and soil microbial communities. Sustainability. 2020;12(22):9669.
42. Singh R, Shukla V, Gupta P, Pandey H, Singh N, Mishra V. Recent advances in nanobioremediation: A step toward sustainable environment. J Environ Chem Eng. 2022;10(3):107329.
43. Das S, Thomas S, Balakrishnan N, Sreekanth TVM. Environmental fate, toxicity and risk management of nanomaterials. Curr Opin Green Sustain Chem. 2021;29:100459.
44. Li M, Pokhrel S, Jin X, Madler L, Damoiseaux R, Hoek EMV. Stability, bioavailability, and toxicity of engineered nanoparticles in the environment. Sci Total Environ. 2020;722:137614.
45. Sharma P, Bhatt D, Zaidi MG, Saradhi PP, Khanna PK, Arora S. Silver nanoparticle-mediated enhancement in growth and antioxidant status of Brassica juncea. Appl Biochem Biotechnol. 2020;160(3):643–50.
46. Hussain CM, Mitra S, Das S. Nanotechnology in environmental monitoring and remediation: Challenges and future outlook. Environ Sci Pollut Res. 2017;24(28):22217–31.
47. Zhou C, Wang J, Li T, Yu J, Yang C, Xu L, et al. The fate and transport of engineered nanoparticles in the environment: Implications for risk assessment. Environ Int. 2018;119:1–9.
48. Crane M, Scott-Fordsmand JJ. Toxicity testing under environmentally relevant conditions: Practical considerations. Environ Toxicol Chem. 2012;31(2):267–70.
49. Patra JK, Das G, Fraceto LF, Campos EVR, Rodriguez-Torres MDP, Acosta-Torres LS, et al. Nano based drug delivery systems: Recent developments and future prospects. J Nanobiotechnol. 2018;16(1):71.
50. Gupta S, Rai M. Application of nanotechnology in bioremediation: Recent developments, challenges, and future perspectives. Int J Environ Sci Technol. 2023;20:5587–602.
51. United Nations. Transforming our world: The 2030 agenda for sustainable development. New York: UN; 2020.
52. Zhao Y, Wang L, Li X, Liu Y, Huang J, Yu H. Circular economy and nanotechnology: Synergies for sustainable environmental management. J Clean Prod. 2023;389:136040.
53. Yu Y, Zhang H, Lu S, et al. Photocatalytic material–microbe hybrids: applications in pollutant degradation and electron transfer enhancement. Front Bioeng Biotechnol. 2022;10:815181.
54. Bundschuh M, Filser J, Luderwald S, McKee MS, Metreveli G, Schaumann GE, et al. Nanoparticles in the environment: Where do we come from, where do we go to? Environ Sci Eur. 2018;30(1):6.
55. Holden PA, Klaessig F, Turco RF, Priester JH, Rico CM, Avila-Arias H, et al. Evaluation of exposure for engineered nanomaterials in soil and sediment. Environ Sci Technol. 2016;50(9):4587–603.
56. Klaine SJ, Alvarez PJJ, Batley GE, Fernandes TF, Handy RD, Lyon DY, et al. Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. Environ Toxicol Chem. 2008;27(9):1825–51.
57. Maurer-Jones MA, Gunsolus IL, Murphy CJ, Haynes CL. Toxicity of engineered nanoparticles in the environment. Anal Chem. 2013;85(6):3036–49.
58. Keller AA, Lazareva A. Predicted releases of engineered nanomaterials: From global to regional to local. Environ Sci Technol Lett. 2014;1(1):65–70.
59. Hansen SF, Heggelund LR, Revilla Besora P, Mackevica A, Boldrin A, Baun A. Nanoproducts – what is actually available to European consumers? Environ Sci Nano. 2016;3(1):169–80.

60. Nel A, Xia T, Mädler L, Li N. Toxic potential of materials at the nanolevel. Science. 2006;311(5761):622–7.
61. Barrett K, Whelan R, McCarthy S. Environmental justice in the age of nanotechnology. NanoEthics. 2021;15:45–60.
62. Schomberg R. From the ethics of technology towards an ethics of knowledge policy & knowledge assessment. Brussels: European Commission; 2013.
63. Falkner R, Jaspers N. Regulating nanotechnologies: Risk, uncertainty and the global governance gap. Glob Environ Polit. 2012;12(1):30–55.
64. Aliyari Rad S, Nobaharan K, Pashapoor N, Pandey J, Dehghanian Z, Senapathi V, et al. Nano-Microbial Remediation of Polluted Soil: A Brief Insight. Sustainability. 2023;15(1):876.
65. Yang Z, Shen J. A review: metal and metal oxide nanoparticles for environmental applications. Nanoscale. 2025;17:15068–85.
66. Ayilara MS, Adeleye SA, Adewale BA, Ajayi OS, Olanrewaju MO, Adegbite OS, et al. Types, mechanisms, and factors affecting microbial bioremediation of pollutants. Egypt J Biol Pest Control. 2023;33:51.
67. Unimke A, Okezie O, Mohammed SE, Mmuoegbulam AO, Abdulahi S, Ofon UA, et al. Microbe–plant–nanoparticle interactions: role in bioremediation of petroleum hydrocarbons. Water Sci Technol. 2024;90(10):2870–93.