Review Article

Engineered Nanoparticles in Soil Ecosystems: Impacts on Micro and Macro-Organisms, Benefits, and Risks

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ABSTRACT

The application of engineered nanoparticles (ENPs) in agriculture has garnered significant attention due to their potential to enhance soil health, nutrient availability, and plant growth. ENPs interact with soil ecosystems by modulating microbial diversity, influencing macro-organisms, and altering root physiology. While certain nanoparticles improve nutrient uptake and stimulate beneficial microbial activity, others exhibit toxicity that may disrupt soil biodiversity and ecological balance. The effects of ENPs on plant roots range from improved permeability and nutrient absorption to oxidative stress and cellular damage. Their interactions with soil microbiota and macro-organisms highlight the complexity of their ecological impact, necessitating a careful evaluation of their long-term sustainability. This review synthesizes current findings on ENP-soil interactions, emphasizing their dual role as both enhancers and potential stressors within agricultural environments. Future research should focus on mitigating risks associated with nanoparticle accumulation in soil while optimizing their benefits for sustainable agricultural practices.

Introduction

The integration of nanoparticles (NPs) into agricultural practices has been increasingly explored due to their potential to enhance plant growth and soil health. Engineered nanoparticles (ENPs) can modulate soil properties such as pH, nutrient availability, and organic matter decomposition rates, influencing both micro- and macro-organisms within the soil ecosystem [1,2]. Recent studies have highlighted the complex effects of engineered NPs on soil microbial communities and nutrient cycling, with responses ranging from stimulation to inhibition depending on concentration and type. For instance, certain NPs like zinc oxide (ZnO) have shown antimicrobial activity, affecting soil microbiota and potentially altering key microbial functions [3]. The rhizosphere is the soil region surrounding plant roots, where complex interactions between roots and microorganisms occur. The presence of nanoparticles can alter the composition and dynamics of microbial populations in this zone,

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potentially influencing nutrient availability, soil health, and plant development (Figure 1) [4].

The impact of NPs on soil ecosystems is multifaceted. They can improve soil structure by enhancing water retention and aggregate stability, which in turn affects microbial activity and nutrient availability. However, there are concerns regarding the environmental risks associated with NPs accumulation in soils, including potential toxicity to beneficial microorganisms and alterations in soil structure [4, 5].

Understanding the interactions between NPs and soil ecosystems is crucial for harnessing their benefits while mitigating risks. This involves examining how ENPs influence microbial diversity, nutrient cycling, and plant growth, as well as assessing their long-term effects on ecosystem health. The ENPs application in agriculture offers several advantages, including improved nutrient delivery and enhanced stress tolerance in plants. However, the environmental implications of their widespread use necessitate careful evaluation to ensure sustainable agricultural practices. In this context, the role of NPs in modulating soil microorganisms is particularly significant. By altering soil properties and microbial communities, NPs can either promote or inhibit plant growth depending on their concentration and type [6,7].

Moreover, the effects of NPs on macro-organisms, such as insects and other soil fauna, are also critical. These organisms play crucial roles in soil ecosystems, contributing to nutrient cycling and soil structure maintenance. The balance between the benefits and risks of NPs in soil ecosystems is delicate. While they offer potential solutions for improving agricultural productivity, their environmental impact must be carefully managed to prevent unintended consequences [8,9].

This study aims to explore the complex interactions between ENPs and soil ecosystems, focusing on both micro- and macro-organisms. By examining the advantages and risks associated with NPs use, we can better understand how to harness their benefits while ensuring sustainable and environmentally conscious agricultural practices. The exploration of these interactions is crucial for developing strategies that maximize the potential of NPs in enhancing soil health and plant productivity. Understanding the impact of NPs on microorganisms, such as bacteria and fungi, is essential for optimizing nutrient cycling and plant growth. Similarly, assessing their effects on macro-organisms like earthworms and insects helps in maintaining ecosystem balance and biodiversity. The advantages of using NPs include improved nutrient delivery, enhanced plant resistance to diseases, and reduced chemical usage. However, potential risks such as bioaccumulation and toxicity in the food chain must be carefully evaluated. By balancing these factors, we can ensure that NPs applications contribute to sustainable agriculture without compromising environmental integrity.

NPS Effect on Soil Microbiota

Bacteria

Studies have shown that silver NPs (AgNPs) can significantly alter the composition of soil microbial communities. Specifically, AgNPs have been found to decrease the abundance of certain bacterial groups. For instance, exposure to AgNPs has been reported to reduce the populations of *beta-Proteobacteria*, *Acidobacteria*, and *Bacteroidetes*. These changes in microbial community structure can have profound effects on soil health and nutrient cycling, ultimately impacting plant growth and productivity [13].

NPs have the potential to impact on the population of rhizosphere bacteria, affecting both deleterious and beneficial microorganisms. By increasing the richness of rhizosphere microbiota, NPs can indirectly enhance plant nutrient absorption and ultimately promote plant growth [14].

For instance, the application of nano-selenium to pepper plants significantly increased the presence of beneficial microorganisms in the rhizosphere soil. This encompassed various bacterial groups including *Gammaproteobacteria*, *Alphaproteobacteria*, *Bacteroidetes*, *Gemmatimonadetes*, *Deltaproteobacteria*, and *Anaerolineae* [15,16].

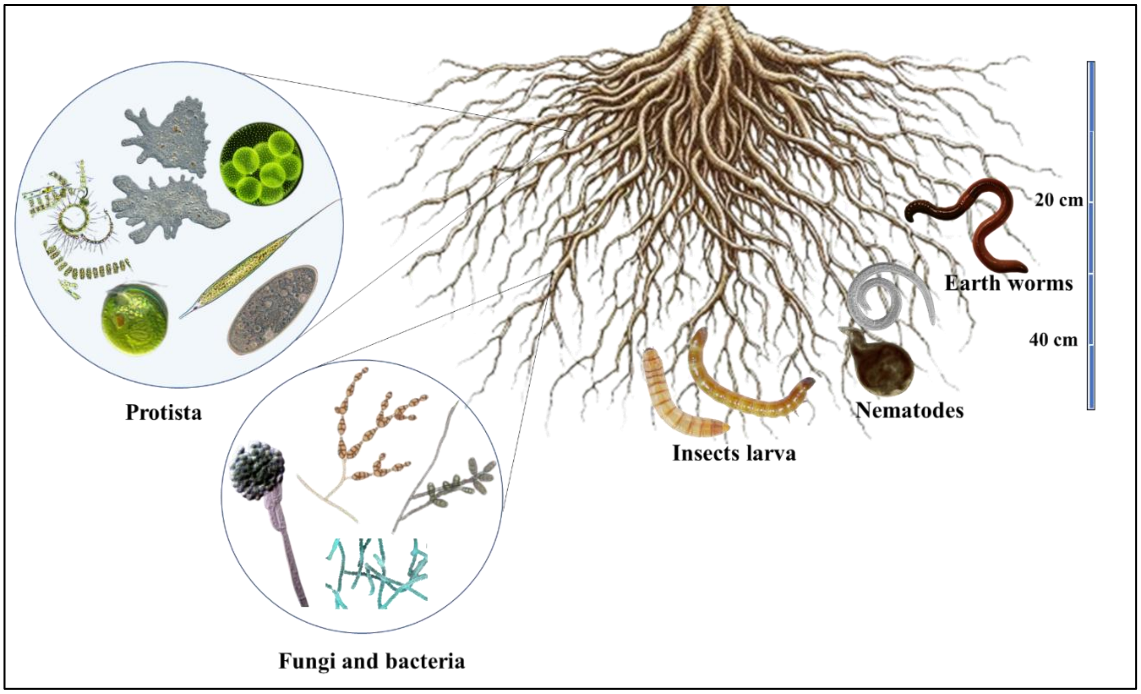

Figure 1: The rhizosphere and associated organisms. The rhizosphere, the soil region surrounding plant roots, hosts a diverse array of macro- and micro-organisms whose interactions play a crucial role in soil health and plant development. NPs may affect these communities, potentially modifying their ecological functions and influencing plant-microbe interactions [10-12]

Nano-selenium influences the rhizosphere microbiome by increasing bacterial diversity and complexity. This shift in microbial community composition is associated with enhanced disease resistance and improved nutrient availability for potatoes. Beneficial microorganisms like *Bacillus* and *Pseudomonas* are promoted, which can aid in nutrient cycling and plant growth. The enhancement of beneficial rhizosphere microorganisms by NPs like nano-selenium highlights their potential role in sustainable agriculture. These beneficial microorganisms can improve soil health by facilitating nutrient cycling, promoting root growth, and increasing plant resilience to environmental stresses [17].

By modulating the microbial community structure in the rhizosphere, NPs can create a more favorable environment for plant growth. The application of nano-selenium fertilizer, particularly when applied twice during the seedling stage, significantly decreased the disease index of potato scab caused by *Streptomyces* spp. This reduction in disease severity is attributed to the enhanced resistance mechanisms in potatoes [18].

Understanding the interactions between NPs and rhizosphere microorganisms is crucial for optimizing their application in agriculture. Research has shown that NPs can stimulate the growth of specific microbial groups that are essential for nutrient assimilation and plant health. For example, *Gammaproteobacteria* and *Alphaproteobacteria* are known for their roles in nitrogen fixation and phosphorus solubilization, which are vital processes for plant nutrition. The use of silica dioxide NPs (SiO_2 NPs) has been found to enhance the production, transport, and release of organic acids in rice roots. These organic acids provide a rich source of carbon for microorganisms in the rhizosphere, resulting in a substantial increase of 15.2-80.5% in beneficial microbes like Proteobacteria and Actinobacteria. This improvement optimizes the bacterial community structure and supports enhanced nitrogen absorption and plant growth, as reported by some studies [19].

The impact of AgNPs and other NPs on soil bacterial communities underscores their potential to reshape microbial dynamics. While beneficial bacteria such as *Gammaproteobacteria* and *Alphaproteobacteria* can enhance nutrient cycling, the reduction of specific bacterial groups due to nanoparticle exposure raises concerns about unintended ecological shifts. The ability of nano-selenium to enrich beneficial microorganisms highlights the dual role of ENPs in promoting plant health while necessitating careful assessment of their long-term effects on microbial diversity. Further research should focus on optimizing ENP formulations to minimize negative disruptions while maximizing agricultural benefits. The contrasting effects of nanoparticles on soil bacteria underscore a dual role: while AgNPs may disrupt microbial communities and impair soil functions, nano-selenium and SiO_2 NPs appear to promote beneficial microbial shifts that support plant health. These findings suggest that optimized NP formulations could be tailored, balancing targeted antimicrobial effects with the stimulation of advantageous rhizosphere bacteria. Further research is needed to determine the optimal concentrations and application timings to minimize unintended ecological shifts while maximizing agronomic benefits.

Fungi

NPs can have both positive and negative effects on soil fungi, depending on their type, concentration, and environmental conditions.

Soil Pathogenic Micro-Fungi

Metallic NPs, Ag, ZnO, and copper oxide (CuO) NPs, exhibit potent antifungal properties against a wide range of plant pathogenic fungi. These NPs can effectively damage fungal cell walls, disrupt membrane integrity, and inhibit spore germination, thereby significantly reducing fungal growth and proliferation [20].

Interestingly, certain fungi can biologically synthesize AgNPs, providing an environmentally friendly method for producing antifungal agents. Fungus-synthesized AgNPs have shown substantial antifungal activity against *R. solani*, reducing its radial growth and disease incidence in plants. For instance, *Trichoderma harzianum* has been utilized to produce AgNPs that effectively inhibit the growth of pathogenic fungi such as *Fusarium fujikuroi* and *Rhizoctonia solani* [21,22].

Additionally, studies have demonstrated the antifungal efficacy of NPs like $Ni_{0.5}Al_{0.5}Fe_2O_4$ against *Fusarium oxysporum*, a common soil-borne pathogen [23].

The antifungal efficacy of metallic NPs presents a promising alternative for controlling plant pathogens. The biological synthesis of AgNPs by certain fungi suggests a sustainable method for nanoparticle production with reduced environmental concerns. However, the widespread application of antifungal NPs demands caution, as excessive use may inadvertently disturb fungal community balance, including beneficial species essential for soil health. Future studies should explore precise nanoparticle dosages and delivery methods to mitigate collateral damage while enhancing disease control strategies.

Mycorrhiza

Certain ENPs, such as Ag and iron oxide NPs (FeO NPs), have been demonstrated to exert negative effects on mycorrhizal fungi. Specifically, AgNPs can lead to a decrease in mycorrhizal colonization, biomass, and diversity [24,25].

The adverse effects of NPs on mycorrhizal fungi can be attributed to their ability to adhere to fungal cell surfaces, causing physical damage to cell walls and membranes. This interaction increases membrane permeability, blocks water channels, and ultimately leads to cell death. The cytotoxic effects of NPs are often concentration-dependent, with higher concentrations typically resulting in more pronounced inhibitory effects. However, at lower concentrations, some NPs may not exhibit adverse effects and could potentially stimulate mycorrhizal growth. Additionally, certain mycorrhizal fungi have been found to alleviate the phytotoxic effects of specific NPs. For example, arbuscular mycorrhizal fungi (AMF) can mitigate the negative impacts of FeO NPs [26] and copper

(Cu) based NPs on plants by enhancing nutrient uptake and reducing oxidative stress. This symbiotic relationship highlights the potential for mycorrhizal fungi to play a protective role against NPs-induced stress in plants [27].

Although some ENPs have been shown to exert detrimental effects on mycorrhizal fungi, emerging evidence demonstrates that AMF can mitigate the phytotoxic effects of metal-based nanoparticles, thereby offering a potential protective mechanism for plants. This mitigation occurs through multiple pathways: AMF can enhance nutrient and water uptake, bolster plant defense responses against oxidative stress, and create a more resilient root zone through improved soil aggregation and organic matter retention. In doing so, AMF not only counteracts the negative impacts of excessive ENP accumulation, but also promotes plant growth and soil health under challenging environmental conditions [25,26].

This interaction underscores the importance of shifting from assessments that focus solely on the isolated toxicity of ENPs to evaluations that consider the broader context of microbial symbiosis. The complex interplay between ENPs and mycorrhizal fungi reveals that toxicity outcomes can differ dramatically when microbial relationships are taken into account. Traditional toxicity models may fail to capture these dynamics, potentially underestimating the buffering capacity of beneficial symbionts. Therefore, future studies should incorporate microbial compatibility assays and functional assessments that examine how ENPs interact within the network of soil biota [26,27].

Sustainable nanoparticle applications must integrate these insights by developing protocols and formulations that prioritize mycorrhizal compatibility. By ensuring that ENP treatments preserve or even enhance beneficial symbioses, we can maintain essential soil processes such as nutrient cycling and water absorption, which are critical for plant health and productivity. Ultimately, adopting a symbiosis-focused approach in nanoparticle research and application will facilitate the development of nanotechnologies that support agricultural productivity while safeguarding vital ecosystem functions.

Nematodes

ENPs exert their nematicidal effects through multiple biochemical pathways. A primary mechanism involves the generation of reactive oxygen species (ROS), which overwhelm nematodes' antioxidant defenses, leading to oxidative damage of lipids, proteins, and cellular structures [28] (Figure 2).

AgNPs demonstrate particular efficacy, in this regard, inducing proteotoxicity and lipid peroxidation while simultaneously triggering genotoxic effects such as DNA fragmentation and upregulation of DNA repair genes like rad-51 and cep-1 in Caenorhabditis elegans. Cross-kingdom genetic impacts have been observed, with green silver NPs (GSN) synthesized from Ulva lactuca algae altering DNA profiles in eggplants (*Solanum melongena*) through RAPD and EST marker analyses [29,30].

Reproductive suppression in nematodes occurs through two primary mechanisms: egg hatching inhibition, where AgNPs achieve 100% suppression at concentrations as low as 0.05 ppm, and developmental blockage, in which CuNPs at 20 µg/mL effectively prevent embryogenesis in *Meloidogyne graminicola*. These processes highlight the potential of engineered NPs in disrupting nematode reproduction and population dynamics [31].

ENPs enhance plant resilience through systemic acquired resistance mechanisms, as demonstrated by GSN treatments that increased eggplant shoot biomass by 69.44% while reducing root-knot nematode populations. Advanced delivery systems utilizing tobacco mosaic virus-derived spherical NPs enable targeted pesticide delivery to the rhizosphere, enhancing nematicidal efficacy without soil contamination [30,31].

The environmental profile of ENPs shows promise, with biogenic variants such as those synthesized from Euphorbia tirucalli latex combining nematicidal activity (85% mortality at 200 ppm) with biodegradability. However, multigenerational studies reveal size-dependent ecological impacts – 10 nm AgNPs reduce *C. elegans* lifespan by 28.8% across three generations, while 2 nm particles primarily affect fertility [28,32].

The robust nematicidal effects of ENPs underscore their potential as powerful tools in managing nematode pests. However, while the targeted disruption of nematode reproduction and enhanced plant resilience are promising, the multigenerational ecological impacts and size-dependent toxicities of these nanoparticles raise concerns. The development of advanced, controlled delivery systems represents a crucial step toward mitigating these unintended consequences. Future research must focus on striking a balance between maximizing nematicidal efficacy and ensuring long-term environmental safety, thereby safeguarding both the productivity of agricultural systems and the integrity of soil ecosystems.

Protista

Oxidative Stress and Cellular Disruptions

ENPs induce oxidative stress in protists primarily through the generation of reactive oxygen species (ROS), which overwhelm cellular antioxidant defenses. This imbalance results in lipid peroxidation, protein damage, and DNA fragmentation [33,34]. For instance, AgNPs disrupt metabolic pathways in mixotrophic protists such as *Poterioochromonas malhamensis* by altering protein expression related to energy metabolism and photosynthesis [35]. The toxicity of ENPs is heavily influenced by their size and surface properties. Smaller nanoparticles (e.g., 10 nm AgNPs) generally generate higher ROS levels and cause more pronounced cellular damage due to their increased surface area-to-mass ratio [33,36]. Additionally, ENPs can impair nutrient uptake in algae by adsorbing to cell surfaces or mimicking essential nutrients, further compromising cellular function.

Bioaccumulation and ecological implications

The exposure to ENPs has been shown to reduce protist population growth and reproductive success. For example, $AgNO_3$ at 3 μg/L decreased *Poterioochromonas malhamensis* cell numbers under dark conditions, whereas light exposure mitigated some of these adverse effects through metabolic adaptation [35,37]. Beyond direct toxicity, ENPs can bioaccumulate in protists due to their small size and high surface reactivity. Positively charged nanoparticles, in particular, exhibit stronger adsorption to cell membranes, leading to enhanced cellular uptake [30]. Protists can also act as vectors for ENP transfer within aquatic food webs. Nanoplastics and metal-based ENPs that accumulate in microalgae are subsequently ingested by zooplankton, reducing survival rates in higher trophic levels and destabilizing microbial loop interactions [2,38]. Although biogenic nanoparticles, such as those derived from plant latex, may be less persistent in the environment, concerns remain regarding their sublethal effects on non-target organisms. Long-term and multigenerational studies have reported significant impacts, including reduced lifespan and altered genetic expression in exposed protist populations [33]. Given the complexity of ENP interactions, standardized toxicity assessment methods under environmentally relevant conditions are essential. Future research should aim to quantify ENP concentrations in natural water bodies and evaluate chronic exposure effects on microbial communities. Moreover, optimizing ENP parameters, such as size and concentration, will be essential for balancing agricultural benefits with ecological safety [39,40]. Further research should prioritize long-term assessments of ENP interactions with protists to better understand the broader ecological implications.

NPs Effect on Soil Macro-Organisms

NPs effect on earthworms

The exposure to gold (Au) and AgNPs triggers oxidative stress in earthworms (*Eisenia fetida*), as evidenced by increased glutathione S-transferase levels, decreased catalase levels, and increased malondialdehyde concentrations. This oxidative stress can lead to cellular damage and disrupt normal physiological functions. Both AuNPs and AgNPs can cause DNA modifications and repress the expression of genes involved in defense and stress responses, even at low concentrations. This suggests that NPs can interfere with genetic processes and potentially impair the ability of earthworms to respond to environmental challenges [41].

Exposure to ZnO NPs, either alone or combined with microplastics, has been linked to increased weight loss and mortality in earthworms. High concentrations of polyethylene microplastics, such as 50 g/kg, can significantly increase mortality and hinder growth over several weeks [42].

Moreover, microplastics can impair earthworm reproduction by reducing the number of cocoons and juveniles, even at lower concentrations, highlighting the sensitivity of reproductive endpoints to microplastic exposure. Microplastics can cause physical harm to the gut lining of earthworms, potentially allowing them to enter the coelomic cavity and disrupt nutrient absorption. Additionally, microplastics can adsorb contaminants like heavy metals and organic pollutants, increasing their bioavailability and toxicity to earthworms [43].

The susceptibility of earthworms to oxidative stress induced by NPs highlights a potential ecological risk, as these organisms play a crucial role in soil aeration, nutrient cycling, and organic matter decomposition. The combined impact of ZnO NPs and microplastics raises concerns about synergistic toxicity effects that could disrupt soil fauna populations. Long-term studies should explore the adaptive mechanisms earthworms may deploy to counteract nanoparticle-induced damage, as well as strategies for developing eco-friendly ENPs that minimize harm to beneficial soil organisms.

NPs effect on soil insects and larvae

Studies have shown that metallic NPs like ZnO and Ag can exhibit potent insecticidal properties against various insect larvae. For instance, ZnO NPs have been effective against cabbage moth larvae (*Pieris brassicae*) at concentrations as low as 200 mg/L, achieving 100% mortality within 72 hours [44], AgNPs can cause developmental problems, mortality, and weight reduction in insects by inducing oxidative stress and disrupting cellular functions [45]. Silica NPs can cause physical abrasion to insect mouthparts, leading to reduced feeding efficiency and starvation. This effect has been observed in pests like *Tribolium castaneum* [46]. NPs can also affect insect larvae indirectly by altering plant physiology or soil microbial communities. For instance, silica NPs may enhance the attraction of natural enemies by influencing herbivore-induced plant volatiles [47].

The potent insecticidal properties of metallic and silica NPs suggest promising applications for pest management in agriculture. However, their unintended consequences, such as developmental disruptions and weight reduction, necessitate further investigation into species-specific toxicity thresholds. The indirect effects of NPs on insect behavior and physiology, particularly through interactions with plant volatiles, offer an intriguing avenue for integrated pest control strategies. Future research should focus on optimizing NP formulations to enhance pest suppression while preserving beneficial insect populations.

NPs effect on plant roots

Root morphology alterations: ENPs can significantly influence root architecture by modifying root length, branching patterns, and overall biomass. Studies indicate that certain NPs, such as carbon-based nanomaterials, promote root elongation by enhancing auxin signaling, whereas metal oxide NPs may inhibit growth due to toxicity effects [16]. The interaction between ENPs and root cells can lead to changes in cell wall composition, affecting root development and nutrient acquisition [48].

Nutrient absorption: Metal oxide NPs, including ZnO and TiO_2, have been shown to enhance nutrient uptake by increasing root permeability and facilitating ion exchange with soil minerals. These NPs can improve the bioavailability of essential nutrients, such as phosphorus and nitrogen, leading to improved plant growth. However, excessive accumulation of ENPs may disrupt ion homeostasis, potentially leading to nutrient imbalances [16].

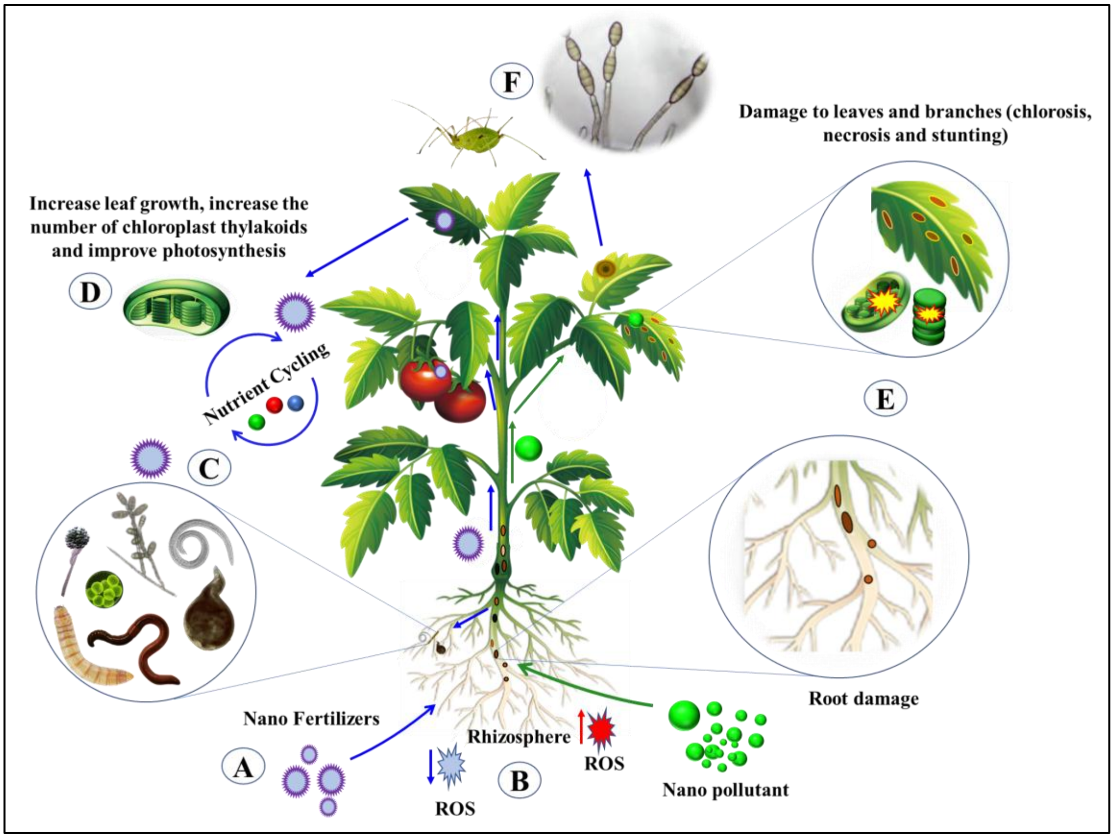

Figure 2: Effects of NPs on micro- and macro-organisms. **A.** NPs, including nano-agrochemicals and environmental pollutants, can be absorbed by plant tissues via root uptake and interactions within the rhizosphere, **B.** the internalization of NPs may modulate oxidative stress in root tissues, either amplifying or mitigating ROS levels, **C.** NPs can influence the composition and abundance of rhizosphere bacteria and microorganisms, potentially altering microbial community dynamics, **D.** by integrating into the nutrient cycle, NPs may enhance leaf development and chlorophyll biosynthesis, potentially improving photosynthetic efficiency. **E.** Certain NPs may induce structural damage to plant tissues, negatively impacting leaf integrity and chlorophyll stability, and **F.** Following translocation to aerial tissues, NPs have been observed to mitigate the occurrence of plant diseases and pest infestations, potentially enhancing plant resistance mechanisms

Oxidative stress and toxicity: High concentrations of ENPs can induce oxidative stress in root cells by generating ROS, leading to lipid peroxidation, protein oxidation, and DNA damage. This oxidative imbalance impairs root function, reducing water and nutrient uptake efficiency. Some studies indicate that plants activate antioxidant defense mechanisms, including superoxide dismutase (SOD) and catalase (CAT), to counteract ENP-induced toxicity [49-51]. For example, aluminum oxide NPs (Al_2O_3 NPs) at concentrations of 50-100 mg/L increased hydrogen peroxide (H_2O_2) levels in *Neslia arvensis* roots by 40%, although antioxidant enzymes mitigated oxidative stress at higher concentrations (1000 mg/L) [52]. Similarly, polyacrylic acid-coated nanoceria (PNC) reduced H_2O_2 by 18.9% in *Arabidopsis* primary roots and superoxide (O_2^-) levels by 88.5% in lateral roots, promoting healthier root development [53].

Translocation to aerial parts: Once absorbed by roots, ENPs can be transported to shoots and leaves via the xylem, affecting overall plant physiology. Studies have demonstrated that NPs can accumulate in leaf tissues, impacting photosynthetic efficiency and stomatal function. The extent of translocation depends on nanoparticle size, surface charge, and plant species, with smaller NPs exhibiting higher mobility within vascular tissues [54,55] (Figure 2).

The ENPs effect on root morphology, nutrient absorption, and oxidative stress responses, as well as translocation to aerial parts highlights their dual potential as growth enhancers and stress inducers. While certain NPs improve root architecture and nutrient assimilation, others, particularly metal oxides, pose toxicity risks that may compromise plant resilience. The observed antioxidant defense mechanisms suggest that plants can adapt to moderate ENP exposure, but excessive accumulation may disrupt cellular homeostasis. The nanoparticles translocation to aerial tissues raises additional concerns regarding long-term physiological effects, requiring further investigation into safe concentration thresholds. Future research should focus on optimizing nanoparticle formulations to balance their agricultural benefits with potential environmental and physiological risks.

Challenges and Future Directions

Despite the promising benefits of engineered nanoparticles (ENPs) in soil ecosystems, several challenges currently hinder their widespread implementation. Environmental and ecotoxicological concerns remain paramount. Although ENPs can enhance plant growth and improve soil microbial communities, their persistence in soils may lead to unintended consequences such as disruptions in microbial diversity, alterations in nutrient cycles, and toxic effects on macro-organisms, including earthworms and beneficial insects [56,57].

Furthermore, the potential biomagnification of ENPs through food chains raises additional concerns about impacts on higher trophic levels. A major challenge is the lack of standardized guidelines for ENP application in agriculture. Variability in nanoparticle synthesis, size, surface charge, and concentration complicates toxicity assessments, emphasizing the need for establishing safe exposure limits and eco-friendly formulations. The complex mechanisms underlying ENP interactions with soil organisms, ranging from oxidative stress induced by metal-based nanoparticles to shifts in microbial metabolic pathways and altered nutrient absorption in plant roots, require further investigation to clarify how different physicochemical properties influence biological responses. While laboratory studies have demonstrated the effectiveness of ENPs, their transition to large-scale agricultural application faces economic and technical hurdles. The optimization of synthesis methods, improvements in product stability and formulation, and the development of cost-effective, biodegradable alternatives to metallic ENPs are critical steps for enabling practical field deployment [58,59].

Looking forward, future research should concentrate on several key areas. First, there is a need for eco-friendly NPs design: developing biodegradable ENPs with minimal environmental persistence represents a promising strategy for sustainable agricultural applications. Alternatives such as biogenic nanoparticles derived from plant extracts or produced via microbial synthesis are particularly promising due to their reduced toxicity. Second, research should focus on engineering targeted and controlled release mechanisms. Smart delivery systems, such as polymer-based coatings, bio-responsive nanoparticles, and virus-derived nanocarriers, could optimize the release of ENPs in soil, enhancing efficacy while minimizing environmental exposure [60].

Third, multigenerational and long-term studies are essential to assess the impacts of ENPs on soil biodiversity and ecosystem functions over extended periods. Such studies should examine effects on microbial succession, nutrient cycling, and overall soil health. The integration of ENPs with emerging technologies, including AI-driven soil monitoring and remote sensing systems, offers opportunities to enable real-time assessment of nanoparticle effects on soil ecosystems and to facilitate predictive ecological modeling. Finally, effective policy development and risk assessment require collaboration between governments, regulatory agencies, and research institutions. Establishing comprehensive, globally standardized guidelines—focusing on risk assessment, safe concentration limits, and robust environmental monitoring protocols—is vital to ensure the responsible use of ENPs in agriculture [61,62].

Together, these research directions and policy initiatives will be fundamental to maximizing the benefits of ENPs while mitigating their associated risks.

Conclusion

The integration of engineered nanoparticles (ENPs) into agricultural systems presents both promising opportunities and significant challenges. Their ability to enhance soil health, nutrient availability, and microbial activity can lead to improved plant growth and productivity. However, their interactions with soil microbiota, macro-organisms, and plant roots indicate that their effects are highly dependent on nanoparticle type, concentration, and environmental conditions. ENPs can stimulate microbial processes, supporting beneficial interactions within the rhizosphere, but they also pose risks, such as microbial toxicity and alterations in soil biodiversity. Similarly, their impact on macro-organisms, including nematodes and soil invertebrates, demonstrates potential applications in pest management, while raising concerns about unintended disruptions in ecological balance. Their effect on plant roots further underscores their dual role, enhancing nutrient uptake while potentially inducing oxidative stress or disrupting natural defense mechanisms. Given these complexities, the responsible use of ENPs in agriculture requires a nuanced approach. Future research should focus on understanding the long-term environmental impacts of nanoparticle accumulation in soil ecosystems, as well as strategies for mitigating toxicity while maximizing benefits. Sustainable agricultural applications of ENPs should be guided by comprehensive risk assessments, regulatory frameworks, and interdisciplinary studies that ensure their safe and effective deployment. Balancing innovation with ecological responsibility will be crucial in determining whether ENPs can be harnessed for sustainable agricultural advancements without compromising ecosystem integrity. Continued investigations into their behavior across various soil environments and biological systems will be essential to unlocking their full potential while minimizing the relevant risks.

Conflict of Interest

The authors declared that there are no conflicts of interest in this work.

Authors' Contributions

Conceptualization, J.F.Q and A.Y: methodology, J.F.Q: writing -original draft preparation, J.F.Q and S.A.M.J: writing -review and editing, and J.F.Q: design Figures and editing. All authors have read and agreed to the published version of the manuscript.

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