Egyptian Journal of Soil Science
http://ejss.journals.ekb.eg/

Nanoecology: Exploring Engineered Nanoparticles' Impact on Soil Ecosystem Health and Biodiversity

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NANOTECHNOLOGY is a growing field that explores the interactions between engineered nanoparticles and ecosystems, with a focus on soil health and biodiversity. Engineered nanoparticles are intentionally designed at the nanoscale and offer unique properties and diverse applications, making them increasingly prevalent in consumer products and industrial processes. However, their release into the environment has raised concerns about potential ecological consequences, particularly their impacts on soil health. Studies have shown that engineered nanoparticles can have complex effects on soil microbial communities and nutrient cycling, with responses ranging from positive to adverse. Additionally, their ability to be absorbed and translocated by plants brings upon questions about their potential bioaccumulation in food chains and their effects on higher trophic levels. Understanding these intricate interactions is crucial for developing sustainable nanotechnology applications that can benefit agriculture and environmental remediation without compromising the ecosystem health. Nanoecology is an emerging field that requires attention to ethical and regulatory considerations in the use of nanomaterials. To ensure that these advanced technologies contribute positively to the ecosystem, researchers and policymakers must address these aspects. By understanding the complex interactions between nanoparticles and ecosystems, nanoecology offers the potential for innovative solutions that promote sustainable coexistence between nanotechnology and the natural world. This study specifically focuses on the relationship between engineered nanoparticles and soil health profiling. It provides a concise overview of this relationship, emphasizing the importance of responsible nanoparticle use. Additionally, the study highlights the need for monitoring soil health in soils contaminated with nanoparticles. Overall, this research underscores the significance of considering ethical and regulatory factors in the use of nanomaterials. It also emphasizes the importance of understanding the impact of nanoparticles on soil health and the need for responsible practices in their application.

Keywords: Engineered nanoparticles, soil health, biodiversity, ecosystem interactions, sustainable nanotechnology.

1. Introduction

Nanotechnology is a growing field that studies the relationship between engineered nanoparticles and ecosystems, particularly in agriculture. The engineered nanoparticles have both positive and negative impacts on soil microbial populations and nutrient cycling. Their ability to be uptaken and translocated by plants raises concerns about their potential bioaccumulation in food chains (Abdalla et. al. 2023). Understanding the interactions between nanoparticles and soil components is essential for responsible

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Received: 15/07/2024; Accepted: 27/09/2024
DOI: 10.21608/EJSS.2024.304704.1814

and sustainable use in agriculture. Nanoparticles can affect soil texture, structure, aggregation, pH, cation exchange capacity (CEC), nutrient availability, water holding capacity, and hydraulic conductivity (El-Henawy et al, 2024). They can also influence the abundance and activity of beneficial soil microbes, such as mycorrhizal fungi and nitrogen-fixing bacteria, which form mutualistic associations with plant roots, enhancing nutrient uptake and promoting plant growth. Soil contamination due to the accumulation of engineered nanoparticles raises concerns about the potential risks of soil contamination (Darwesh & Matter, 2022).

Monitoring and remediation strategies are essential to manage nanoparticle-contaminated soils and minimize potential environmental risks. The ecotoxicological effects of engineered nanoparticles on soil organisms are essential to understand the potential risks associated with their presence in soil ecosystems (El-Ramady et al, 2020). Soil invertebrates, such as earthworms, mites, springtails, and nematodes, play a crucial role in soil processes and are indicators of soil health. The potential for nanoparticles to enter food chains and the wider environment raises concerns about their ecological impacts and long-term environmental fate (El-Ramady et al, 2024). The responsible use of engineered nanoparticles in agriculture is essential to protect soil ecosystems, human health, and the environment (Faizan et al, 2023; Nofal et al, 2024). Regulations and guidelines should be established to govern the production, application, and disposal of nanoparticle products, taking into account factors such as nanoparticle characteristics, application rates, application methods, and potential environmental impacts. An education and awareness programs are essential for informed decision-making and responsible practices in the agricultural sector

With an emphasis on soil health and biodiversity, nanotechnology is a developing subject that investigates the relationships between manmade nanoparticles and ecosystems. Because of their special qualities and wide range of uses, engineered nanoparticles are becoming more and more common in industrial and consumer goods. Concerns regarding possible ecological repercussions have been raised, nevertheless, following their discharge into the environment. Research has indicated that modified nanoparticles can impact soil microbial populations and nutrient cycling in both favourable and adverse ways. Their capacity for absorption and translocation by plants also raises the question of whether they could bioaccumulate in food chains and have an impact on higher trophic levels (Denisse et al, 2021). Determining how these interactions work is essential for the formulation of sustainable nanotechnology applications to improve agriculture and environmental amendments without jeopardizing the ecosystem health. In order to guarantee that these cutting-edge technologies contribute to a robust and functioning ecosystem, researchers and policymakers must address the ethical and regulatory elements of nanomaterial usage as nanoecology gains speed. In soils contaminated with nanoparticles, soil health monitoring is also crucial.

It is of utmost importance to comprehend the impacts of engineered nanoparticles on the profiling of soil health in order to guarantee the sustainable use of nanoparticles in agriculture and protect soil ecosystems for future generations (Fatima et al, 2021; Rehmanullah et al, 2020). Soil health plays a critical role in sustainable agriculture as it encompasses the physical, chemical, and biological characteristics of soil that facilitate plant growth, nutrient cycling, and overall ecosystem functioning. Well-maintained soils foster optimal root development, nutrient accessibility, water penetration, and microbial activity, thereby enhancing crop productivity, resilience to environmental pressures, and decreasing dependence on external resources (Tripathi et al, 2023). These nanoparticles exhibit distinct physicochemical characteristics, including a large surface area, reactivity that depends on their size, and the ability to modify their surface properties. These attributes make them highly promising tools for various agricultural applications (Ndaba et al, 2022; Babu et al, 2022; Al-Mamun et al, 2021; Das and Beegum, 2022; Yadav et al, 2023).

In agriculture, engineered nanoparticles have shown potential in areas such as crop protection, nutrient management, and soil remediation. They can be tailored to encapsulate agrochemicals, facilitating their targeted delivery to plants and reducing their off-target effects (Das and Beegum, 2022). Additionally, nanoparticles can be used as nano-fertilizers, enabling controlled and efficient nutrient release to enhance plant nutrient uptake and reduce nutrient losses (Yadav et al, 2023; Padhan et al, 2024). Moreover, nanoparticles have been investigated for their potential to enhance soil remediation processes, such as the degradation of organic pollutants or the immobilization of heavy metals (Ahmed et al, 2021). Understanding the interactions between engineered nanoparticles and soil components is critical for assessing their potential impacts on soil health. Engineered nanoparticles, upon application to soil, can interact with soil particles, organic matter, and microbial communities, leading to alterations in soil physicochemical properties, nutrient dynamics, and microbial activity (Kumar et al, 2021; Ogunkunle et al, 2021). These interactions can have both positive and negative consequences for soil health. While nanoparticles may enhance nutrient availability, improve water retention, or promote beneficial microbial activities, they can also cause unintended effects, such as soil structure destabilization or toxicity to soil organisms (Banerjee and van der Heijden, 2023; Hartmann and Six, 2023; Trivedi et al, 2022; Salem and Husen, 2023).

Therefore, a comprehensive understanding of nanoparticle-soil interactions is essential to guide their responsible and sustainable use in agriculture. Recent research has shed light on the interactions between engineered nanoparticles and soil components. Studies have explored the effects of nanoparticles on soil aggregation and stability (Zhanget al, 2021; Munir et al 2023). The dynamics of nutrient availability and cycling and the structure and diversity of soil microbial communities (Wilhelm et al, 2023; Sambangi et al, 2022). These investigations have provided valuable insights into the mechanisms and potential implications of nanoparticle-soil interactions.

2. Physicochemical Properties of Soils and Engineered Nanoparticles

Engineered nanoparticles can have significant effects on soil texture, structure, and aggregation, thereby influencing the physical properties of soils. The interactions between nanoparticles and soil particles can lead to changes in soil particle size distribution and affect soil texture. For instance, the addition of nanoparticles can modify the clay content and alter the soil texture, potentially impacting soil water retention and nutrient availability (Sun et al, 2022; Sun et al, 2021; Khan et al, 2022). Furthermore, engineered nanoparticles can influence soil structure and aggregation, which are vital for soil porosity, water movement, and root growth. The presence of nanoparticles in soil can alter soil aggregation dynamics, affecting the stability of soil aggregates and pore structure These changes can impact soil aeration, water infiltration, and nutrient transport, with potential implications for plant growth and nutrient uptake. Several studies have reported the effects of engineered nanoparticles on soil structure and aggregation. For example, research has shown that the addition of metal-based nanoparticles can influence soil aggregation by promoting the formation of stable aggregates (Hartmann and Six, 2023; Jansson and and Hofmockel, 2020;Védère et al, 2022; Patel et al, 2021; Shahane and Shivay, 2021; Zhou et al, 2021). Other studies have demonstrated that certain nanoparticles, such as carbon-based nanoparticles, can enhance soil aggregation and improve soil structure (Zhou et al, 2020; AlObaid et al, 2022).

2.1 Effects on Soil pH, Cation Exchange Capacity (CEC), and Nutrient Availability

Engineered nanoparticles can also influence soil pH, CEC, and nutrient availability. The addition of nanoparticles to soil can alter the soil pH by affecting the release and adsorption of hydrogen ions. Different types of nanoparticles may exhibit varying effects on soil pH, depending on their surface properties and chemical composition (Singh et al, 2021; Suazo-Hernández et al, 2023). Furthermore, engineered nanoparticles can interact with soil colloids and affect CEC that measure the soil's ability to retain and exchange cations, which are essential for nutrient availability to plants. Nanoparticles can adsorb onto soil colloids and modify their surface charge, influencing the CEC and potentially affecting nutrient retention and release. The presence of engineered nanoparticles in the soil can also impact nutrient availability. Nanoparticles may influence the sorption, desorption, and mobility of nutrients, affecting their bioavailability to plants. Metal-based nanoparticles, can enhance the retention and release of nutrients in the soil, potentially leading to improved nutrient availability for plants (Ogunkunle et al, 2021; Gui et al, 2021). Conversely, certain nanoparticles may interact with nutrients and reduce their bioavailability, posing challenges for plant nutrient uptake. Several studies have investigated the effects of engineered nanoparticles on soil pH, CEC, and nutrient availability. For example, research has demonstrated that the addition of iron-based nanoparticles can alter soil pH and CEC, affecting nutrient retention and release (Wohlmuth et al, 2022). Other studies have examined the influence of nanoparticles on the availability of specific nutrients, such as phosphorus or nitrogen, and reported contrasting effects depending on nanoparticle properties (Rahman et al, 2022; Hazarika et al, 2022).

2.2 Alterations in Soil Water Holding Capacity and Hydraulic Conductivity

Engineered nanoparticles can impact soil water holding capacity and hydraulic conductivity, affecting water availability and movement in soils. Nanoparticles can influence soil water-holding capacity by altering soil aggregation and pore structure, thereby affecting water retention and availability for plant uptake (Ahmed et al, 2021; Dinesh et al, 2012). Moreover, the presence of nanoparticles in soil can influence soil hydraulic conductivity, which is a measure of the soil's ability to transmit water. The interactions between nanoparticles and soil particles can modify soil pore spaces, affecting water movement and infiltration rates. These changes in hydraulic conductivity can impact soil drainage, water availability, and plant root growth (Salam et al, 2023). Several studies have explored the effects of engineered nanoparticles on soil water-holding capacity and hydraulic conductivity. For instance, research has shown that the addition of nanoparticles, such as silicon-based nanoparticles, can enhance soil water-holding capacity and improve water retention (Ahmed et al, 2021; Wang et al, 2023; Singh et al, 2021). Other studies have investigated the influence of nanoparticles on soil hydraulic conductivity and reported varying effects depending on nanoparticle properties and application rates (Kumar et al, 2021; Salem and Husen, 2023; Pérez-Hernández et al., 2020).

By understanding the influence of engineered nanoparticles on the physicochemical properties of soils, including soil texture, structure, pH, CEC, nutrient availability, water holding capacity, and hydraulic conductivity, we can better comprehend their potential impacts on soil health and agricultural sustainability. This knowledge is crucial for the responsible and informed application of nanoparticles in agriculture, allowing us to harness their benefits while minimizing any adverse effects on soil functions and crop productivity (Figure 1). Engineered Nanoparticles and Soil Microbial Communities and Impacts of Engineered Nanoparticles on Soil Microbial Abundance, Diversity, and Activity; Engineered nanoparticles have the potential to influence soil microbial communities, which play a critical role in nutrient cycling, organic matter decomposition, and overall soil health. The introduction of nanoparticles to soil can directly or indirectly affect the microbial abundance, diversity, and activity. Studies have shown that engineered nanoparticles can influence the soil microbial abundance, with varying effects depending on nanoparticle properties and concentrations. Silver nanoparticles, have been found to exert antimicrobial effects, reducing microbial populations in soil (Kumar et al, 2021; Banerjee and van der Heijden, 2023; Wijesooriya et al, 2023).

Conversely, other nanoparticles, like carbon-based nanoparticles, have been shown to stimulate microbial growth and increase microbial biomass (Wu *et. al.* 2023). In addition to abundance, nanoparticles can also impact microbial diversity in soil. The exposure to nanoparticles may lead to shifts in the relative abundance of different microbial taxa, altering the microbial community composition. These changes in microbial diversity can have implications for ecosystem functioning and nutrient cycling processes (Hartmann and Six, 2023; Trivedi et. al., 2020). Furthermore, engineered nanoparticles can affect microbial activity in soil. Microbial activity, as measured by enzyme activities or metabolic processes, can be influenced by the presence of nanoparticles. Some nanoparticles may enhance microbial enzyme activities, leading to increased nutrient mineralization and decomposition rates, while others may inhibit microbial metabolic processes, affecting nutrient cycling dynamics (Khan et al, 2021; Wagg et al, 2021).

Shifts in Microbial Community Composition and Functional Gene Expression; The introduction of engineered nanoparticles to soil can induce shifts in microbial community composition. These changes may be attributed to direct interactions between nanoparticles and microbial cells or indirect effects mediated through alterations in soil physicochemical properties. Engineered nanoparticles can influence the relative abundance of specific microbial groups, such as bacteria, fungi, or archaea, which can impact the functional capabilities of the soil microbial community (Khan et al, 2022; Zhu et al, 2022). Furthermore, the presence of nanoparticles in soil can affect the expression of functional genes involved in key microbial processes. Functional genes related to nutrient cycling, such as those encoding nitrogenase enzymes for nitrogen fixation or enzymes involved in carbon degradation, may be modulated by the presence of nanoparticles. These changes in gene expression can have cascading effects on nutrient availability, soil fertility, and ecosystem functioning (Philippot et al, 2023; Wijesooriya et al, 2023). Recent studies have employed molecular techniques, such as high-throughput sequencing and metagenomics, to investigate the impacts of engineered nanoparticles on the microbial community composition and functional gene expression. For example, research has demonstrated that the addition of nanoparticles can lead to shifts in the relative abundance of specific microbial taxa and alterations in functional gene expression related to nutrient cycling processes (Wu et al, 2022).

2.3 Potential Effects on Mycorrhizal Fungi and Nitrogen-Fixing Bacteria

Engineered nanoparticles can also influence the abundance and activity of beneficial soil microbes, such as mycorrhizal fungi and nitrogen-fixing bacteria. Mycorrhizal fungi form mutualistic associations with plant roots, enhancing nutrient uptake and promoting plant growth. Studies have shown that certain nanoparticles can affect the colonization and activity of mycorrhizal fungi in soil, potentially influencing plant nutrient acquisition and ecosystem productivity (Ahmed et al, 2021; Dinesh et al, 2012; Khanna et al, 2021; Banerjee and van der Heijden, 2023; Mathur et al, 2023; Das et al, 2022). Similarly, nitrogen-fixing bacteria, such as rhizobia, play a crucial role in nitrogen cycling by converting atmospheric nitrogen into a form available for plant uptake.

Engineered nanoparticles can interact with nitrogen-fixing bacteria and impact their survival, activity, or symbiotic interactions with plants. These effects can have implications for plant nitrogen nutrition and soil fertility (Zhu et al, 2023). Research has begun to unravel the potential effects of engineered nanoparticles on beneficial soil microbes. For instance, studies have examined the impacts of nanoparticles on mycorrhizal colonization and functionality, as well as the survival and effectiveness of nitrogen-fixing bacteria under nanoparticle exposure (Salam et al, 2023). These investigations contribute to our understanding of the ecological consequences of nanoparticle-soil microbial interactions. By comprehending the impacts of engineered nanoparticles on soil microbial communities, including changes in abundance, diversity, activity, shifts in community composition, functional gene expression, and effects on beneficial soil microbes, we can better assess the implications for soil health, nutrient cycling, and plant-microbe interactions (Wu et al, 2022; Wu *et al,* 2023; Colvin, 2003). This knowledge is essential for informed decision-making regarding the application and management of nanoparticles in agricultural systems.

3.Nutrient Dynamics and Engineered Nanoparticles

Engineered nanoparticles can have profound effects on nutrient dynamics in soil, influencing the availability, mobility, and uptake of essential nutrients by plants. The interactions between nanoparticles and soil nutrients can impact nutrient transformations, sorption-desorption processes, and nutrient bioavailability.

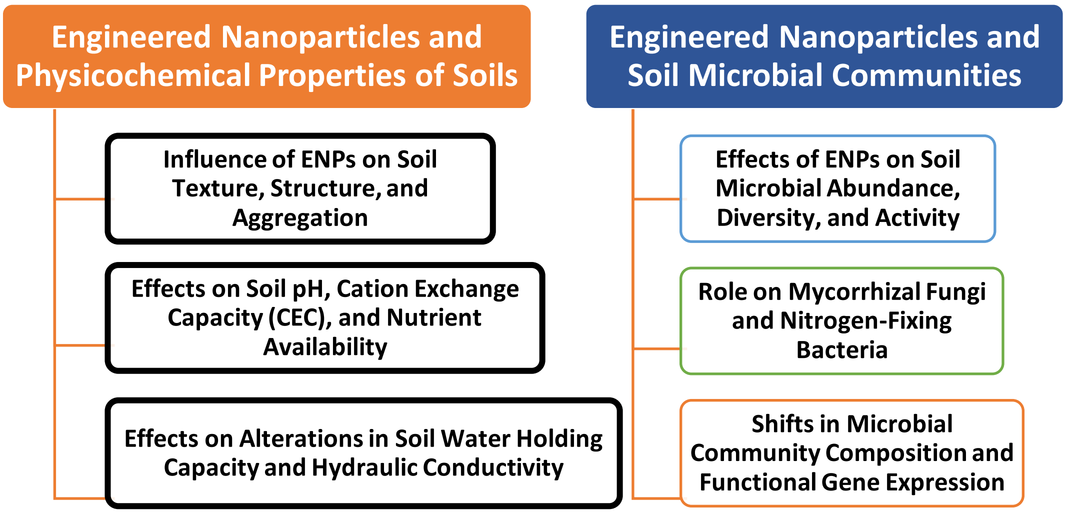

Fig. 1. Effects of ENPs in the biogeochemical properties of soil.

Fig. 2. Nutrient Dynamics of soil and Engineered Nanoparticles.

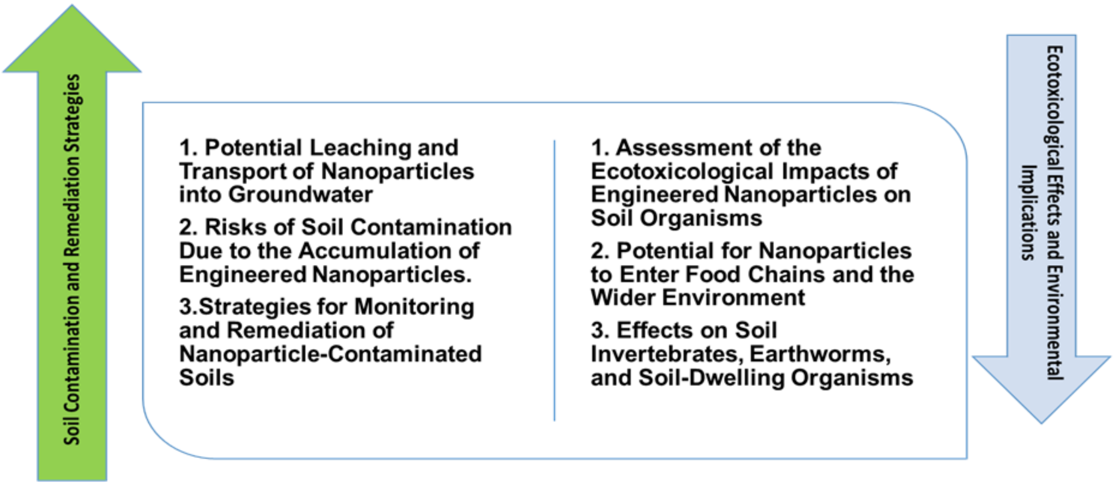

Fig. 3. Soil Contamination, Remediation and Ecological Effect of ENPs.

The addition of engineered nanoparticles to soil can affect nutrient availability by altering nutrient sorption and desorption processes. Nanoparticles can adsorb onto soil colloids and modify their surface properties, influencing the retention and release of nutrients. Some nanoparticles, such as iron-based nanoparticles, have been shown to enhance the retention and availability of certain nutrients, while others may interact with nutrients and reduce their bioavailability (Sun et al, 2022; Vishwakarma et al, 2023). Furthermore, engineered nanoparticles can influence nutrient mobility in soil. Nanoparticles can affect the movement and leaching of nutrients by altering soil water dynamics and transport processes (Figure 2). For example, the presence of nanoparticles can modify soil water holding capacity, hydraulic conductivity, and solute transport properties, which can impact nutrient movement and availability for plant uptake (Castan et al, 2021). The interactions between engineered nanoparticles and plants can also influence nutrient uptake. Nanoparticles can affect the physiological processes involved in nutrient acquisition, including root morphology, nutrient uptake kinetics, and nutrient transport within plants (Yu et al, 2018; Chanu et al, 2021). Some nanoparticles have been reported to enhance nutrient uptake efficiency and promote plant growth, while others may inhibit nutrient uptake or lead to nutrient imbalances (Ma et al, 2010; Wahab et al, 2023; Rai et. al. 2018; Barkataki and Singh, 2019).

3.1 Interactions among Nanoparticles and Soil Nutrients

Engineered nanoparticles can interact with various soil nutrients, including nitrogen, phosphorus, and micronutrients, influencing their availability and cycling in soil-plant systems. These interactions can have significant implications for nutrient dynamics and plant nutrition. Nitrogen is a critical nutrient for plant growth, and the interactions between nanoparticles and nitrogen compounds can influence nitrogen availability and transformations in soil. For example, certain nanoparticles can affect nitrogen mineralization, nitrification, and denitrification processes, potentially leading to altered nitrogen availability for plants (Salem and Husen, 2023; Khan et al, 2023). Phosphorus is another essential nutrient for plants, and its availability can be influenced by nanoparticles. Engineered nanoparticles can interact with soil phosphorus compounds, affecting phosphorus sorption-desorption processes and solubility. These interactions can influence phosphorus availability to plants and its potential for leaching into water bodies (El Attar et al, 2022**)**. Moreover, engineered nanoparticles can interact with micronutrients, such as iron, zinc, copper, and manganese. These interactions can affect the bioavailability and speciation of micronutrients in soil, potentially influencing their uptake by plants and plant nutritional status. For example, the addition of nanoparticles may enhance the availability of certain micronutrients, leading to improved plant nutrient acquisition (Peng et al, 2022; Singh et al, 2021).

3.2 Implications for Nutrient Cycling and Plant Nutrient Acquisition

The impacts of engineered nanoparticles on nutrient dynamics have significant implications for nutrient cycling and plant nutrient acquisition in agricultural systems. Understanding these implications is essential for optimizing nutrient management strategies and ensuring sustainable crop production. The alterations in nutrient availability, mobility, and uptake caused by nanoparticles can influence nutrient cycling processes in soil. Changes in nutrient availability can affect nutrient mineralization, immobilization, and transformations by soil microorganisms, influencing nutrient cycling rates and dynamics. These changes can impact nutrient availability for plants and the overall nutrient cycling efficiency in the ecosystem (Vishwakarma et al, 2023). Furthermore, the interactions between nanoparticles and soil nutrients can influence plant nutrient acquisition and nutrient use efficiency. Nanoparticles may enhance nutrient uptake efficiency by promoting root growth, increasing nutrient bioavailability, or improving nutrient transport within plants (Wahab et al, 2023; Mandal et al, 2023). On the other hand, nanoparticles may inhibit nutrient uptake or induce nutrient imbalances, affecting plant growth and nutrient utilization (Sharma et al, 2023). The implications of nanoparticle-induced changes in nutrient dynamics extend beyond individual plants to ecosystem-level nutrient cycling processes. The modifications in nutrient availability, mobility, and plant nutrient acquisition can affect plant productivity, nutrient-use efficiency, and the cycling of nutrients within agricultural systems (Chauhan, 2023) . Therefore, it is crucial to consider the effects of engineered nanoparticles on nutrient dynamics when developing sustainable nutrient management strategies.

4. Soil Contamination and Remediation Strategies

The increasing use of engineered nanoparticles raises concerns about the potential risks of soil contamination. As nanoparticles are released into the environment through various sources, including industrial activities and agricultural practices, they can accumulate in soils and pose potential hazards to ecosystems and human health (Hegazy et al, 2024). Engineered nanoparticles can accumulate in soils through direct application or deposition from air and water sources. The accumulation of nanoparticles in soil can result in increased soil nanoparticle concentrations over time (Abdurrahman et al, 2020). This accumulation may lead to adverse effects on soil properties, nutrient availability, and soil biota, ultimately impacting ecosystem health and functioning (Bathi et al, 2022; Giese et al., 2018; Rajput et al, 2020; Rajput et al, 2020; Rajput et al, 2021). The risks associated with soil contamination by engineered nanoparticles depend on several factors, including nanoparticle properties, concentrations, exposure duration, and interactions with soil components. Some nanoparticles may have toxic effects on soil organisms, including microbes, plants, and soil fauna, leading to alterations in soil ecological processes and nutrient cycling dynamics (Adhikari and Dharmarajan, 2022).

Additionally, the potential for nanoparticles to interact with other pollutants in soil, such as heavy metals or organic contaminants, can exacerbate the risks of soil contamination. Synergistic or antagonistic interactions between nanoparticles and other pollutants can influence their mobility, bioavailability, and toxicity, amplifying the overall environmental risks (Ghai and Kaur, 2022). The leaching and transport of nanoparticles from soil into groundwater is a significant concern due to the potential for groundwater contamination. Engineered nanoparticles can migrate through soil pores, preferential flow paths, and water channels, reaching underlying groundwater resources. The mobility of nanoparticles in soil depends on their physicochemical properties, soil characteristics, and hydrological conditions (Hou et al, 2023). Nanoparticles with smaller sizes and higher surface reactivity are generally more mobile and prone to leaching than larger nanoparticles or bulk materials (Sun et al, 2021; Sun et al, 2022). The leaching of nanoparticles into groundwater can result in the contamination of drinking water supplies and aquatic ecosystems. Once in groundwater, nanoparticles can undergo transformation and interact with dissolved ions, colloids, and organic matter, potentially affecting water quality and the biogeochemical processes in aquatic systems (Maurya et al, 2020: and Maurya et al, 2023).

Understanding the potential leaching and transport of nanoparticles in soil is crucial for assessing the risks associated with groundwater contamination (Madanayake et. al. 2022). Factors such as soil properties, land use practices, irrigation methods, and rainfall patterns can influence nanoparticle mobility and transport pathways, highlighting the importance of site-specific assessments and monitoring (Figure 3). The development of monitoring and remediation strategies is essential for managing nanoparticle-contaminated soils and minimizing potential environmental risks. Effective monitoring allows for the detection, quantification, and spatial mapping of nanoparticle distribution in soils, providing valuable information for risk assessment and decision-making. Monitoring techniques for nanoparticle-contaminated soils include advanced analytical methods such as spectroscopy, microscopy, and molecular techniques. These techniques enable the characterization of nanoparticle properties, their fate and transport in soil, and their interactions with soil components and biota (Adhikari, 2021; Alazaiza et al, 2021). Remediation of nanoparticle-contaminated soils aims to reduce nanoparticle concentrations, mitigate risks, and restore soil quality. Various remediation strategies can be employed, depending on the nature and extent of the contamination (Gil-Díaz et al, 2022). These strategies include physical, chemical, and biological approaches. Physical methods for remediation may involve techniques such as soil washing, electrokinetics, or filtration, which aim to separate and remove nanoparticles from soil matrices (Trivedi et al, 2022). Chemical methods may involve the use of sorbents or amendments to enhance nanoparticle immobilization or promote their transformation into less toxic forms. Biological methods may utilize the activities of soil microorganisms or plants to degrade or sequester nanoparticles in soil (Hou et al., 2023; Gil-Díaz et al., 2022; Trivedi et al., 2022; Baragaño et al., 2020; Zheng et al., 2022; Kumar et al., 2022; Ren et al., 2022; Samarajeewa et al., 2021; Kumar et al., 2018; Cifuentes-Croquevielle et al., 2020). The selection of remediation strategies should consider site-specific conditions, cost-effectiveness, and potential ecological impacts. Integrated approaches that combine multiple techniques or leverage natural attenuation processes can provide more sustainable and efficient remediation solutions.

5. Ecotoxicological Effects and Environmental Implications

The assessment of the ecotoxicological impacts of engineered nanoparticles on soil organisms is essential for understanding the potential risks associated with their presence in soil ecosystems. Numerous studies have investigated the effects of nanoparticles on soil organisms, including microorganisms, invertebrates, and plants, using standardized laboratory tests and field studies (Kumar et al, 2022; Ren et al, 2022). The ecotoxicological effects of nanoparticles on soil organisms can vary depending on various factors such as nanoparticle properties, concentrations, exposure duration, and specific organism sensitivities. For example, silver nanoparticles have been shown to exert toxic effects on soil bacteria, fungi, and invertebrates, while carbon-based nanoparticles may have minimal effects or even beneficial effects on soil microorganisms (Abdurrahman et al, 2020). The interactions between nanoparticles and soil organisms can result in physiological and biochemical alterations, disruption of biological processes, and changes in the structure and functioning of soil ecosystems. These effects can impact nutrient cycling, organic matter decomposition, and plant-soil interactions, with potential consequences for soil health and ecosystem sustainability (Hartmann and Six, 2023).

Soil invertebrates, including earthworms, mites, springtails, and nematodes, play crucial roles in soil processes and are indicators of soil health. Engineered nanoparticles can have direct or indirect effects on these soil-dwelling organisms, affecting their survival, reproduction, behaviour, and ecological functions (Hegazy et al, 2024). Earthworms, in particular, are often used as model organisms for ecotoxicological studies due to their sensitivity and ecological significance. Research has shown that certain nanoparticles can alter earthworm behaviour, reproduction, and growth, as well as influence soil nutrient cycling processes mediated by earthworm activities (Banerjee and van der Heijden, 2023; Hartmann and Six, 2023). Other soil invertebrates, such as mites and springtails, can also be affected by nanoparticle exposure. These organisms play vital roles in nutrient cycling, organic matter decomposition, and soil structure formation. Studies have indicated that nanoparticles can influence the abundance, activity, and functional diversity of these soil invertebrates, potentially leading to changes in soil processes and ecosystem functions (Delgado-Baquerizo et al, 2020; Wurst et al, 2018).

The potential for nanoparticles to enter food chains and the wider environment raises concerns regarding their environmental implications. Once introduced into soil ecosystems, nanoparticles can be taken up by plants and subsequently transferred to higher trophic levels, including herbivores, predators, and humans. Plant uptake of nanoparticles can occur through the roots, leading to their accumulation in different plant tissues . The transfer of nanoparticles through trophic levels raises questions about their potential impacts on organism health, ecological interactions, and the overall integrity of food chains (Keller et al, 2023). Furthermore, nanoparticles released from soil can be transported through water bodies or atmospheric deposition, potentially reaching aquatic ecosystems, sediments, or even remote areas far from the original source. This widespread distribution raises concerns about their ecological impacts and long-term fate in the environment (Bundschuh et al, 2019; Singh et al, 2023). Understanding the potential for nanoparticles to enter food chains and the wider environment requires comprehensive studies that assess the bioaccumulation, biomagnification, and trophic transfer of nanoparticles in different ecosystems. Additionally, investigating the long-term effects on organism health, population dynamics, and ecosystem functioning will provide valuable insights into the ecological consequences of nanoparticle exposure (Kumar et al, 2022).

6. Assessing Soil Health in the Presence of Engineered Nanoparticles

Assessing soil health is crucial for sustainable agriculture and environmental management. With the increasing use of engineered nanoparticles and their potential impacts on soil ecosystems, it is essential to develop approaches for evaluating soil health in the presence of these nanoparticles. Traditional soil health assessment methods typically include the measurement of physical, chemical, and biological properties of soil. These indicators provide valuable insights into soil fertility, structure, nutrient availability, and microbial activity. However, in the presence of engineered nanoparticles, additional considerations are necessary to understand their potential effects on soil health (Abd-Elzaher et al. 2022). One approach for profiling soil health in the presence of engineered nanoparticles is to integrate nanoparticle-specific indicators with traditional soil health assessments. These indicators may include the measurement of nanoparticle concentrations, size distributions, and their interactions with soil components. Analytical techniques such as spectroscopy, microscopy, and molecular techniques can be employed to characterize nanoparticle behaviour in soil (Banerjee and van der Heijden 2023; Wilhelm et al. 2023).

In addition to nanoparticle-specific indicators, it is crucial to consider the interactions between nanoparticles and traditional soil health indicators. For example, engineered nanoparticles may affect soil pH, nutrient availability, organic matter decomposition rates, and microbial community structure. Therefore, the interpretation of traditional soil health indicators should account for the potential influence of nanoparticles on these parameters (Ren et al, 2022). To assess soil health in the presence of engineered nanoparticles, it is essential to integrate traditional soil health indicators with nanoparticle-specific considerations. This integration provides a comprehensive understanding of soil functioning and potential nanoparticle-induced alterations. Physical indicators such as soil texture, structure, and aggregation can be evaluated using conventional methods (Wilhelm et al, 2023). However, the potential impact of nanoparticles on soil physical properties should be considered. For instance, nanoparticles can influence soil aggregation and pore structure, affecting water infiltration and nutrient movement (Ren et al, 2022). Chemical indicators, including soil pH, nutrient content, and CEC, are critical for assessing soil fertility and nutrient availability (AbdelRahman, 2023; AbdelRahman and Arafat, 2020; AbdelRahman, and Tahoun, 2019; AbdelRahman et al. 2021; AbdelRahman et al. 2022). In the presence of nanoparticles, their influence on soil pH and nutrient interactions should be accounted for the interpretation of these indicators. Additionally, the potential for nanoparticle-induced nutrient imbalances or deficiencies should be considered.

6.1 Engineered Nanoparticles and Soil-Dwelling Organisms

Biological indicators, such as microbial biomass, enzyme activities, and community composition, provide insights into soil microbial functions and nutrient cycling (Banerjee and van der Heijden 2023). However, nanoparticles can alter microbial communities and their activities. Therefore, nanoparticle-specific considerations, such as evaluating microbial sensitivity to nanoparticles and their effects on microbial functions, should be integrated into the assessment of soil biological indicators (Hartmann and Six, 2023). Assessing soil health in nanoparticle-contaminated soils presents several challenges and requires future research efforts to address knowledge gaps and improve assessment methodologies. One challenge is the need for standardized protocols and guidelines specifically tailored for nanoparticle-contaminated soils. The development of standardized approaches will enhance comparability across studies and improve the reliability of soil health assessments in the presence of engineered nanoparticles. Another challenge is the dynamic nature of nanoparticle-soil interactions and their long-term effects on soil health (Wilhelm et al. 2023). Nanoparticles can undergo transformation and aggregation processes in soil, altering their behaviour and potential impacts (Figure 4). Long-term studies are necessary to understand the persistence and fate of nanoparticles in soil and their consequences for soil health over extended periods. Furthermore, there is a need for interdisciplinary collaborations among scientists from different fields, including nanotechnology, soil science, ecotoxicology, and agronomy. Such collaborations will foster the development of comprehensive assessment approaches that consider the complex interactions between nanoparticles and soil components.

6.2 Sustainable Soil Management and Nanoparticle Applications

The responsible use of engineered nanoparticles in agriculture is essential to ensure the protection of soil ecosystems, human health, and the environment. While nanoparticles offer potential benefits in agricultural practices, such as enhanced nutrient availability, improved pesticide delivery, and increased crop productivity, their use should be guided by careful considerations and risk assessments (Vishwakarma et al. 2023). To promote responsible use, regulations and guidelines should be established to govern the production, application, and disposal of nanoparticle-based products in agriculture. These regulations should consider factors such as nanoparticle characteristics, application rates, application methods, and potential environmental impacts. Additionally, labelling requirements and standardized testing protocols can provide information on nanoparticle properties, behaviour, and potential risks. Education and awareness programs are crucial to ensure that farmers, agronomists, and other stakeholders are informed about the potential benefits and risks associated with nanoparticle applications (Bastida et al. 2021). This knowledge will enable informed decision-making and responsible practices in the agricultural sector. Collaboration between researchers, regulators, industry, and farmers is vital for developing and implementing guidelines that support the responsible use of engineered nanoparticles in agriculture (Ensor and Bruin, 2022).

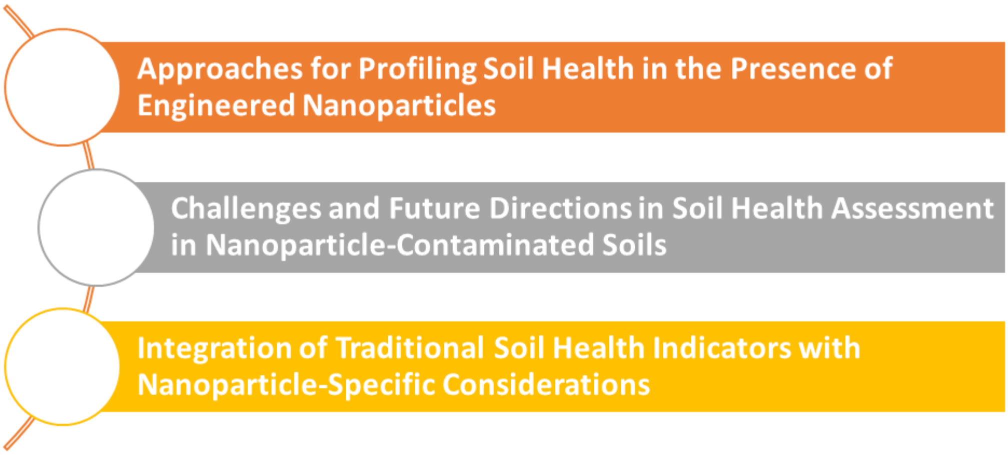

Fig. 4. Assessing Soil Health in the Presence of Engineered Nanoparticles.

7. Soil Health Profiling with Engineered Nanoparticles

Strategies for minimizing potential risks and maximizing the benefits of engineered nanoparticles in agriculture can be implemented at different stages of nanoparticle life cycles, from production to application and disposal (Vishwakarma et al. 2023). In the production phase, efforts should be made to optimize nanoparticle synthesis methods to minimize environmental impacts. Green synthesis approaches, such as using bio-based materials or eco-friendly methods, can reduce the potential for hazardous by-products or waste generation (Wahab et al. 2023). During nanoparticle application, precision agriculture techniques can be employed to ensure targeted and efficient delivery. This reduces the number of nanoparticles required and minimizes the risk of unintended environmental exposure. The use of encapsulation techniques or controlled-release formulations can also enhance the stability and controlled release of nanoparticles, reducing their potential for off-target effects (Vishwakarma et al. 2023).

Proper waste management and disposal practices should be implemented to prevent nanoparticle release into the environment. Recycling, treatment, or safe disposal of nanoparticle-containing materials can minimize the potential for environmental contamination. Collaboration with waste management authorities and the development of specific disposal protocols for nanoparticle-containing products are important for reducing risks (Bradford et al. 2022 Suman et al. 2022). The integration of nanoparticle-based approaches with soil conservation practices and sustainable soil management can enhance the overall effectiveness and environmental sustainability of agricultural systems. Nanoparticles can be used in combination with traditional soil conservation practices, such as conservation tillage, cover cropping, and crop rotation, to improve soil health and productivity. For example, nanoparticle-based formulations can be applied in conjunction with organic amendments to enhance nutrient availability and promote soil organic matter accumulation. This integration can lead to improved soil structure, increased water-holding capacity, and reduced erosion (Lehmann et al. 2022).

The application of nanoparticles can be targeted to address specific soil constraints or limitations. For instance, nanoparticles can be used to remediate contaminated soils, enhance nutrient use efficiency, or mitigate the impacts of abiotic stressors. The selection of nanoparticle types, dosages, and application methods should be based on site-specific conditions, considering factors such as soil properties, crop requirements, and environmental considerations (Ulhassan et al. 2022). Integrating nanoparticle-based approaches with precision agriculture technologies, such as sensor-based nutrient management and site-specific application systems, can optimize the efficiency of nanoparticle use and minimize potential environmental risks. This integration allows for targeted and precise application, reducing overuse and unnecessary environmental exposure (Singh et al. 2021; Zhang et al. 2021).

8. Conclusion and Future Prospective

This research has shown a solar-powered, efficient, eco-friendly, and cost-effective way to remove metals from polluted soil by harnessing plants' inherent ability. According to the Copper-polluted soil remediation findings, *M. lupulina* had considerably greater root growth, and chlorophyll contents at higher copper concentrations. *M. lupulina* has the greatest concentration of copper in their roots. All things considered, the data and observations pointed to *M. lupulina* as a species that can accumulate, a short growth cycle, and high resistance to metal stress. The high BCF and TF values further supported the idea that *M. lupulina* was the best plant species to use for copper phytoextraction, and it remedied the copper -contaminated soil more quickly and in more flushes than the others. It was easy to dispose of the gathered plant biomass above the group part since it was biodegradable. It might be used as a raw material for large-scale composting or phytomining, or as an alternative source of biofuel energy. In addition, residents in the impacted regions could reap the benefits of the natural, risk-free strategy by reducing the levels of harmful metals in agricultural land irrigated with untreated water. Furtherfuture perspectives towards the studied problem of removing copper from contaminated soils using *M.lupulina* L. plant through additive-mediated phytoextraction requires further investigation and practical application for sustainable land rehabilitation. To achieve this, long-term investigations are necessary to assess the effectiveness of this approach over multiple growing seasons. Additionally, optimizing additive dosages and application methods can improve phytoextraction efficiency while minimizing adverse effects on soil biota and plant vitality. Furthermore, studying the interactions between *M.lupulina* L. and contaminated soils at the molecular and microbial level can provide insights into enhancing metal uptake pathways and root exudates, improving remediation efficacy. The feasibility and effectiveness of additive-mediated phytoextraction under real-world conditions should also be validated by utilization different other types of additives like nanoparticles and biochar in laboratory experiments to field-scale applications (El-Ramady et al. 2020; Elramady et al. 2021; Singh et al. 2023; Singh et al. 2023). Finally, integrating phytoextraction with complementary techniques such as phytostabilization and bioremediation may offer sustainable land rehabilitation efforts synergistic benefits. In conclusion, while the current study provides foundational insights, ongoing research is necessary to fully harness the potential of additive-mediated phytoextraction in addressing copper contamination in soils.

List of abbreviations: Not applicable

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

Competing interests: The authors declare that they have no conflict of interest in the publication.

Funding: This work recievd no fund.

Authors' contributions: All the authors contributed equally to this work.

Acknowledgments: The authors are gratuful for their intities to facilitate this work**.**

References

Abdalla, Z., El-Bassiony, A. E. M., El-Ramady, H., El-Sawy, S., &shedeed, S. (2023). Broccoli Biofortification Using Biological Nano- and Mineral Fertilizers of Selenium: A Comparative Study under Soil Nutrient Deficiency Stress. Egyptian Journal of Soil Science, 63(1), 57-66. doi: 10.21608/ejss.2022.176648.1553

AbdelRahman, M.A.E. (2023) An overview of land degradation, desertification and sustainable land management using GIS and remote sensing applications. Rend. Fis. Acc. Lincei, 34, 767–808. https://doi.org/10.1007/s12210-023-01155-3

AbdelRahman, M.A.E. and Arafat, S.M. (2020) An Approach of Agricultural Courses for Soil Conservation Based on Crop Soil Suitability Using Geomatics. Earth Syst Environ 4, 273–285. https://doi.org/10.1007/s41748-020-00145-x

AbdelRahman, M.A.E., and Tahoun, S. (2019). GIS model-builder based on comprehensive geostatistical approach to assess soil quality. Remote Sensing Applications: Society and Environment., Volume 13, January 2019, Pages 204-2014. https://doi.org/10.1016/j.rsase.2018.10.012

AbdelRahman M. A. E., Rehab H. H., Yossif T. M. H. (2021) Soil fertility assessment for optimal agricultural use using remote sensing and GIS technologies. Applied Geomatics. https://doi.org/10.1007/s12518-021-00376-1

AbdelRahman, M.A.E., Saleh, A.M. & Arafat, S.M. (2022) Assessment of land suitability using a soil-indicator-based approach in a geomatics environment. Sci. Rep. 12, 18113. https://doi.org/10.1038/s41598-022-22727-7

Abd-Elzaher, M. A., El-Desoky, M. A., Khalil, F. A., Eissa, M. A., & Amin, A. E.-E. A. (2022). Interactive effects of k-humate, proline and Si and Zn nanoparticles in improving salt tolerance of wheat in arid degraded soils. Egyptian Journal of Soil Science, 62(3), 237-251. https://doi.org/10.21608/ejss.2022.154365.1523

Abdurrahman, H., Ahmed Abdel-Hafeez, A.-N. A., Kamel, G. A.-N., & Ahmed, H. (2020). Assessment and Spatial Distribution of Cadmium, Nickel and Lead within Soils of Sinnours, Fayoum, Egypt. Egyptian Journal of Soil Science, 60(3), 247-261. https://doi.org/10.21608/ejss.2020.31481.1360

Adhikari, T. (2021) Nanotechnology in Environmental Soil Science. In Soil Science: Fundamentals to Recent Advances; Rakshit, A., Singh, S., Abhilash, P., Biswas, A., Eds.; Springer, Singapore,. https://doi.org/10.1007/978-981-16-0917-6_14

Adhikari, T.; Dharmarajan, R. (2022) Nanocontaminants in soil: emerging concerns and risks. Int. J. Environ. Sci. Technol. , 19, 9129–9148. https://doi.org/10.1007/s13762-021-03481-1

Ahmed, B.; Rizvi, A.; Ali, K.; Lee, J.; Zaidi, A.; Khan, M.S.; Musarrat. J. (2021) Nanoparticles in the soil–plant system: a review. Environ Chem Lett., 19, 1545-1609. https://doi.org/10.1007/s10311-020-01138-y

Alazaiza, M.Y.D.; Albahnasawi, A.; Ali, G.A.M.; Bashir, M.J.K.; Copty, N.K.; Amr, S.S.A.; Abushammala, M.F.M.; Al Maskari, T. (2021) Recent Advances of Nanoremediation Technologies for Soil and Groundwater Remediation: A Review. Water , 13, 2186. https://doi.org/10.3390/w13162186

Al-Mamun, R.; Hasan, R.; Ahommed, S.; Bacchu S.; Ali R.; Khan Z.H. (2021) Nanofertilizers towards sustainable agriculture and environment. Environmental Technology & Innovation, 23, 101658. https://doi.org/10.1016/j.eti.2021.101658

AlObaid A.; Rehman K.U.; Andleeb S.; Erinle K.O.; Mahmood A. (2022) Capacity assessment of carbon-based nanoparticles in stabilizing degraded soils. Journal of King Saud University - Science, 34(1), 101716. https://doi.org/10.1016/j.jksus.2021.101716

Babu, S.; Singh, R.; Yadav, D.; Rathore, S.S.; Raj, R.; Avasthe, R.; Yadav, S.K.; Das, A.; Yadav, V.; Yadav, B.; Shekhawat, K.; Upadhyay, P.K.; Yadav, D.K.; Singh, V.K. (2022) Nanofertilizers for agricultural and environmental sustainability. Chemosphere, 292, 133451. https://doi.org/10.1016/j.chemosphere.2021.133451.

Banerjee, S.; van der Heijden, M.G.A. (2023) Soil microbiomes and one health. Nat Rev Microbiol , 21, 6–20. https://doi.org/10.1038/s41579-022-00779-w

Baragaño, D.; Forján, R.; Welte, L.; Gallego, J.L.R. (2020) Nanoremediation of As and metals polluted soils by means of graphene oxide nanoparticles. Sci Rep , 10, 1896. https://doi.org/10.1038/s41598-020-58852-4

Barkataki, M.P.; Singh, T. (2019) Chapter Two - Plant-nanoparticle interactions: Mechanisms, effects, and approaches. Comprehensive Analytical Chemistry, 87, 55-83. https://doi.org/10.1016/bs.coac.2019.09.007.

Bastida, F.; Eldridge, D.J.; García, C.; Png, G.K.; Bardgett, R.D.; Delgado-Baquerizo, M. (2021) Soil microbial diversity–biomass relationships are driven by soil carbon content across global biomes. The ISME J , 15, 2081–2091. https://doi.org/10.1038/s41396-021-00906-0

Bathi, J.R.; Wright, L.; Khan, E. (2022) Critical Review of Engineered Nanoparticles: Environmental Concentrations and Toxicity. Curr Pollution Rep , 8, 498–518 https://doi.org/10.1007/s40726-022-00237-4

Bradford, S.A.; Shen, C.; Kim, H.; Letcher, R.J.; Rinklebe, J.; Ok, Y.S.; Ma, L. (2022) Environmental applications and risks of nanomaterials: An introduction to CREST publications during 2018–2021. Critical Reviews in Environmental Science and Technology, 52(21), 3753-3762. https://doi.org/10.1080/10643389.2021.2020425

Bundschuh, M.; Englert, D.; Rosenfeldt, R.R.; Bundschuh, R.; Feckler, A.; Lüderwald, S.; Seitz, F.; Zubrod, J.P.; Schulz, R. (2019) Nanoparticles transported from aquatic to terrestrial ecosystems via emerging aquatic insects compromise subsidy quality. Sci Rep , 9, 15676. https://doi.org/10.1038/s41598-019-52096-7

Castan, S.; Henkel, C.; Hüffer, T.; Hofman, T. (2021) Microplastics and nanoplastics barely enhance contaminant mobility in agricultural soils. Commun Earth Environ, 2, 193. https://doi.org/10.1038/s43247-021-00267-8

Chanu, N.B.; Alice, A.K.; Thokchom, A.; Sing, M.C.; Chanu, N.T.; Sing Y.D. (2021) Engineered nanomaterial and their interactions with plant–soil system: a developmental journey and opposing facts. Nanotechnol. Environ. Eng. , 6, 36. https://doi.org/10.1007/s41204-021-00130-3

Chauhan, N.S. The Impact of Nanoparticles on Agriculture and Soil, (2023) Chapter 19 - The impact of nanoparticles in agriculture and soil: conclusion and future recommendations. Nanomaterial-Plant Interactions, 403-408. https://doi.org/10.1016/B978-0-323-91703-2.00005-1

Cifuentes-Croquevielle, C.; Stanton, D.E.; Armesto, J.J. (2020) Soil invertebrate diversity loss and functional changes in temperate forest soils replaced by exotic pine plantations. Sci Rep, 10, 7762. https://doi.org/10.1038/s41598-020-64453-y

Colvin, V. (2003) The potential environmental impact of engineered nanomaterials. Nat Biotechnol, 21, 1166–1170 (2003). https://doi.org/10.1038/nbt875

Das S.; Beegum S. (2022) Nanofertilizers for sustainable agriculture. Agricultural Nanobiotechnology, 355-370. https://doi.org/10.1016/B978-0-323-91908-1.00005-5.

Das, P.P.; Singh, K.R.; Nagpure, G.; Mansoori, A.; Singh, R. P.; Ghazi, I.A.; Kumar, A.; Singh, S. (2022) Plant-soil-microbes: A tripartite interaction for nutrient acquisition and better plant growth for sustainable agricultural practices. Environmental Research, 214(1), 113821. https://doi.org/10.1016/j.envres.2022.113821

Darwesh, O., & Matter, I. (2022). Challenges of nanotechnology applications in addressing environmental pollution. Egyptian Journal of Chemistry, 65(2), 275-285. https://doi.org/10.21608/ejchem.2021.86072.4172

Delgado-Baquerizo, M.; Reich, P.B.; Trivedi, C.; (2020) Multiple elements of soil biodiversity drive ecosystem functions across biomes. Nat Ecol Evol , 4, 210–220. https://doi.org/10.1038/s41559-019-1084-y

Denisse V.J.; Roberto S.C.; Hermes P.; Patricio T.A.; Andrea P.; Fabián, F. (2021) Chapter 8 - Influence of nanoparticles on the physical, chemical, and biological properties of soils. Nanomaterials for Soil Remediation, 151-182. https://doi.org/10.1016/B978-0-12-822891-3.00008-6.

Dinesh, R.; Anandaraj, M.; Srinivasan, V.; Hamza. S. (2012) Engineered nanoparticles in the soil and their potential implications to microbial activity. Geoderma, 173–174, 19-27. https://doi.org/10.1016/j.geoderma.2011.12.018

El Attar, I.; Hnini, M.; Taha, K.; Aurag, J. Phosphorus (2022) Availability and its Sustainable Use. J Soil Sci Plant Nutr, 22, 5036–5048. https://doi.org/10.1007/s42729-022-00980-z

El-Henawy, A. S., Khalifa, M. R., Gaheen, S. A., & El-Faramawy, H. (2024). Gypsum and Nano-gypsum effects on certain soil characteristics and sorghum yield under saline-sodic soil conditions. Egyptian Journal of Soil Science, 64(3). https://doi.org/10.21608/ejchem.2021.86072.4172

El-Ramady, H., Brevik, E. C., Abowaly, M., Ali, R., Saad Moghanm, F., Gharib, M. S., Prokisch, J. (2024). Soil degradation under a changing climate: management from traditional to nano-approaches. Egyptian Journal of Soil Science, 64(1). https://doi.org/10.21608/ejss.2023.248610.1686

El-Ramady, H., El-Henawy, A., Amer, M., Omara, A. E.-D., Elsakhawy, T., Elbasiouny, H., El-Mahrouk, M. (2020). Agricultural waste and its nano-management: Mini review. Egyptian Journal of Soil Science, 60(4), 349-364. https://doi.org/10.21608/ejss.2020.46807.1397

Ensor, J.; Bruin, A. (2022) The role of learning in farmer-led innovation. Agricultural Systems, 197, 103356. https://doi.org/10.1016/j.agsy.2021.103356

Fatima, F.; Hashim, A.; Anees, S. (2021) Efficacy of nanoparticles as nanofertilizer production: a review. Environ Sci Pollut Res , 28, 1292–1303. https://doi.org/10.1007/s11356-020-11218-9

Ghai, S.; Kaur, A. (2022) Interaction of Nanoparticles to Soil Pollutants. In The Role of Nanoparticles in Plant Nutrition under Soil Pollution. Sustainable Plant Nutrition in a Changing World; Rajput, V.D., Verma, K.K., Sharma, N., Minkina, T., Eds.; Springer, Cham., Switzerland Baar, Switzerland,. https://doi.org/10.1007/978-3-030-97389-6_13

Giese, B.; Klaessig, F.; Park, B.; Kaegi, B.; Steinfeldt, M.; Wigger, H.; von Gleich, A.; Gottschalk, F. (2018) Risks, Release and Concentrations of Engineered Nanomaterial in the Environment. Sci Rep , 8, 1565. https://doi.org/10.1038/s41598-018-19275-4

Gil-Díaz, M.; Pérez, R.A.; Alonso, J.; Miguel, L.; Diez-Pascual, S.; Lobo, M.C. (2022) Iron nanoparticles to recover a co-contaminated soil with Cr and PCBs. Sci Rep , 12, 3541. https://doi.org/10.1038/s41598-022-07558-w

Gui, X.; Song, B.; Chen, M., Xu, X.; Ren Z.; Li, X.; Cao, X. (2021) Soil colloids affect the aggregation and stability of biochar colloids. Science of The Total Environment, 771(1), 145414. https://doi.org/10.1016/j.scitotenv.2021.145414

Hartmann, M.; Six, J. (2023) Soil structure and microbiome functions in agroecosystems. Nat Rev Earth Environ ,4, 4–18. https://doi.org/10.1038/s43017-022-00366-w

Hazarika, A.; Yadav M.; Yadav D.K.; Yadav, H.S. (2022) An overview of the role of nanoparticles in sustainable agriculture. Biocatalysis and Agricultural Biotechnology, 43, 102399. https://doi.org/10.1016/j.bcab.2022.102399.

Hegazy, R., El-Swaify, Z., & Radwan, A. (2024). Unlocking Soil Remediation Potential: Effects of Chelators on Moringa oleifera Lam. Growth and Soil Health in Heavy Metal Contamination. Egyptian Journal of Agronomy, 46(1), 141-156. DOI: 10.21608/agro.2024.290734.1437

Hou, D., Al-Tabbaa, A.; O'Connor, D.; Hu, Q.; Zhu, Y.G.; Wang, L.; Kirkwood, N.; Ok, Y.S.; Tsang, D.C.W.; Bolan, N.S.; Rinklebe, J. (2023) Sustainable remediation and redevelopment of brownfield sites. Nat Rev Earth Environ , 4, 271–286. https://doi.org/10.1038/s43017-023-00404-1

Faizan, M., Alam, P., Rajput, V., Tonny, S., Yusuf, M., Sehar, S., Adil, M. F., & Hayat, S. (2023). Nanoparticles: An Emerging Soil Crops Saviour under Drought and Heavy Metal Stresses. Egyptian Journal of Soil Science, 63(3), 355-366. doi: 10.21608/ejss.2023.220619.1616

Jansson, J.K.; Hofmockel, K.S. (2020) Soil microbiomes and climate change. Nat Rev Microbiol , 18, 35–46. https://doi.org/10.1038/s41579-019-0265-7

Keller, A.A.; Ehrens, A.; Zheng, Y., Nowack, B. (2023) Developing trends in nanomaterials and their environmental implications. Nat. Nanotechnol. , 18, 834–837. https://doi.org/10.1038/s41565-023-01409-z

Khan, F.; Siddique, A.B.; Shabala, S.; Zhou, M.; Zhao, C. (2023) Phosphorus Plays Key Roles in Regulating Plants' Physiological Responses to Abiotic Stresses. Plants, 12, 2861. https://doi.org/10.3390/plants12152861

Khan, S.T.; Adil, S.F.; Shaik, M.R.; Alkhathlan, H.Z.; Khan, M.; Khan, M. (2022) Engineered Nanomaterials in Soil: Their Impact on Soil Microbiome and Plant Health. Plants, 11(1), 109. https://doi.org/10.3390/plants11010109

Khanna K.; Kohli, S.K.; Handa, N.; Kaur, H.; Ohri, P.; Bhardwaj, R.; Yousaf, B.; Rinklebe, J.; Ahmad, P. (2021) Enthralling the impact of engineered nanoparticles on soil microbiome: A concentric approach towards environmental risks and cogitation. Ecotoxicology and Environmental Safety. 222, 112459. https://doi.org/10.1016/j.ecoenv.2021.112459

Kumar, A.; Sharma, P.K.; Singh, S.; Verma, J.P. (2021) Impact of Engineered Nanoparticles on Microbial Communities, Soil Health and Plants. In Plant-Microbes-Engineered Nano-particles (PM-ENPs) Nexus in Agro-Ecosystems; Singh, P., Singh, R., Verma, P., Bhadouria, R., Kumar, A., Kaushik, M., Eds.; Advances in Science, Technology & Innovation. Springer, Cham, Switzerland Baar, Switzerland, pp. 201-215. https://doi.org/10.1007/978-3-030-66956-0_14

Kumar, C.M. V.; Karthick, V.; Kumar, G.; Inbakandan, D.; Rene, E. R.; Suganya, U.; Embrandiri, A.; Dhas, T. S.; Ravi, M.; Sowmiya, P. (2022) The impact of engineered nanomaterials on the environment: Release mechanism, toxicity, transformation, and remediation. Environmental Research, 212, 113202. https://doi.org/10.1016/j.envres.2022.113202.

Kumar, P.; Burman, U.; Kaul, R.K. (2018) Nanomaterials in Plants, Algae, and Microorganisms, Chapter 19 - Ecological Risks of Nanoparticles: Effect on Soil Microorganisms. Concepts and Controversies, 1, 429-452. https://doi.org/10.1016/B978-0-12-811487-2.00019-0.

Lehmann, J.; Bossio, D.A.; Kögel-Knabner, I.; Rilling, M.C. (2020) The concept and future prospects of soil health. Nat Rev Earth Environ., 1, 544–553. https://doi.org/10.1038/s43017-020-0080-8

Ma, X.; Geisler-Lee, J.; Deng, Y.; Kolmakov, K. (2010) Interactions between engineered nanoparticles (ENPs) and plants: phytotoxicity, uptake and accumulation. Sci Total Environ., 408(16), 3053-3061. https://doi.org/10.1016/j.scitotenv.2010.03.031

Madanayake, N.H.; Perera, N.; Adassooriya, N.M. (2022) Emerging Contaminants in the Environment, Chapter 10 - Engineered nanomaterials: threats, releases, and concentrations in the environment. Challenges and Sustainable Practices, 225-240. https://doi.org/10.1016/B978-0-323-85160-2.00001-9.

Mandal, S.; Gupta, S.K.; Ghorai, M.; Patil, M.T.; Biswas, P.; Kumar, M.; Radha; Gopalakrishnan, A.V.; Mohture, V.M.; Rahman, H.; Prasanth, D.A.; Mane, A.B.; Jha, N.K.; Jha, S.K.; Lal, M.K.; Tiwari, R.K., Dey, A. (2023) Plant nutrient dynamics: a growing appreciation for the roles of micronutrients. Plant Growth Regul , 100, 435–452. https://doi.org/10.1007/s10725-023-01006-z

Mathur P.; Chakraborty, R.; Aftab, T.; Roy, S. (2023) Engineered nanoparticles in plant growth: Phytotoxicity concerns and the strategies for their attenuation. Plant Physiology and Biochemistry, 199, 107721. https://doi.org/10.1016/j.plaphy.2023.107721.

Maurya, S., Abraham, J.S., Somasundaram, S.; Toteja, R.; Makhija, S. (2020) Indicators for assessment of soil quality: a mini-review. Environ Monit Assess , 192, 604. https://doi.org/10.1007/s10661-020-08556-z

Maurya, S.; Pal, P.; Saxena, A.; Zhang, D. (2023) The sources, leaching, remediation, and environmental concerns associated with groundwater salinity. Environ Sci Pollut Res , 30, 103405–103423. https://doi.org/10.1007/s11356-023-29601-7

Munir, N.; Gulzar, W.; Abideen, Z.; Hasanuzzaman, M.; El-Keblawy, A.; Zhao, F. (2023) Plant–Nanoparticle Interactions: Transcriptomic and Proteomic Insights. Agronomy , 13, 2112. https://doi.org/10.3390/agronomy13082112

Ndaba B.; Roopnarain A.; Rama, H.; Maaza, M. (2022) Biosynthesized metallic nanoparticles as fertilizers: An emerging precision agriculture strategy. Journal of Integrative Agriculture, (21, 5), 1225-1242. https://doi.org/10.1016/S2095-3119(21)63751-6

Nofal, E., Menesy, F., Elbably, S., Abd-El Rahman, M., El-Ramady, H., & Prokisch, J. (2024). Response of Kigelia africana (Lam.) Benth Transplants to Nano-NPK and Nano-Chitosan under Salinity Stress. Egyptian Journal of Soil Science, 64(2), 661-672. doi: 10.21608/ejss.2024.267464.1718

Ogunkunle C.O.; Oyedeji S.; Okoro H.K.; Adimula V. (2021) Chapter 6 - Interaction of nanoparticles with soil. Nanomaterials for Soil Remediation, , 101-132. https://doi.org/10.1016/B978-0-12-822891-3.00006-2.

Padhan, S.R.; Kar, I.; Mohanty, A.; Panigrahi, K.K. (2024) Nanofertilizers: Types, Synthesis, Methods, and Mechanisms. In Nanofertilizers for Sustainable Agroecosystems. Nanotechnology in the Life Sciences; Abd-Elsalam, K.A., Alghuthaymi, M.A., Eds.; Springer, Cham. Switzerland Baar, Switzerland,. https://doi.org/10.1007/978-3-031-41329-2_3

Patel, K.F.; Fansler, S.J.; Campbell, T.P.; Bond-Lamberty, B.; Smith, A.P.; RoyChowdhury, T.; McCue, L.A.; Varga, T.; Bailey, V.L. (2021) Soil texture and environmental conditions influence the biogeochemical responses of soils to drought and flooding. Commun Earth Environ, 2, 127. https://doi.org/10.1038/s43247-021-00198-4

Peng, Z.; Liang, C.; Gao, M.; Qiu, Y.; Pan, Y.; Gao, H.; Liu, Y.; Li, X.; Wei, G.; Jiao, S. (2022) The neglected role of micronutrients in predicting soil microbial structure. npj Biofilms Microbiomes , 8, 103 https://doi.org/10.1038/s41522-022-00363-3

Pérez-Hernández, H.; Fernández-Luqueño, F.; Huerta-Lwanga, E.; Mendoza-Vega, J.; José, D.I. (2020) Effect of engineered nanoparticles on soil biota: Do they improve the soil quality and crop production or jeopardize them? Land Degradation & Development, 31(16), 2213-2230. https://doi.org/10.1002/ldr.3595

Philippot, L.; Chenu, C.; Kappler, A.; Rilling, M.C.; Fierer, N. (2023) The interplay between microbial communities and soil properties. Nat Rev Microbiol . https://doi.org/10.1038/s41579-023-00980-5

Rahman, S.U.; Wang, X.; Shahzad, M.; Bashir, O.; Li Y.; Cheng, H. (2022) A review of the influence of nanoparticles on the physiological and biochemical attributes of plants with a focus on the absorption and translocation of toxic trace elements. Environmental Pollution, 310(1), 119916. https://doi.org/10.1016/j.envpol.2022.119916

Rai, P.K.; Kumar, V.; Lee, S.; Raza, N.; Kim, K.; Ok, K.S.; Tsang, D.C.W. (2018) Nanoparticle-plant interaction: Implications in energy, environment, and agriculture. Environment International, 119, 1-19. https://doi.org/10.1016/j.envint.2018.06.012.

Rajput, V.; Minkina, T. Mazarji, M.; Shende, S.; Sushkova, S.; Saglara, S.; Burachevskaya, M.; Chaplygin, V.; Singh, A.; Jatav, A. (2020) Accumulation of nanoparticles in the soil-plant systems and their effects on human health. Annals of Agricultural Sciences, 65(2), 137-143. https://doi.org/10.1016/j.aoas.2020.08.001.

Rajput, V.; Minkina, T.; Sushkova, S., Behal, A.; Maksimov, A.; Blicharska, E.; Ghazaryan, K.; Movsesyan, H.; Barsova, N. (2020) ZnO and CuO nanoparticles: a threat to soil organisms, plants, and human health. Environ Geochem Health, 42, 147–158. https://doi.org/10.1007/s10653-019-00317-3

Rajput, V.D.; Singh, A.; Singh V.A.; Minkina, T.M.; Sushkova, S. (2021) Chapter 4 - Impact of nanoparticles on soil resource. Nanomaterials for Soil Remediation, 65-85. https://doi.org/10.1016/B978-0-12-822891-3.00004-9.

Rehmanullah; Muhammad, Z.; Inayat, N.; Majeed, A. (2020) Application of Nanoparticles in Agriculture as Fertilizers and Pesticides: Challenges and Opportunities. In New Frontiers in Stress Management for Durable Agriculture; Rakshit, A., Singh, H., Singh, A., Singh, U., Fraceto, L., Eds.; Springer, Singapore., pp. 281-293. https://doi.org/10.1007/978-981-15-1322-0_17

Ren, W.; Liu, H.; Teng, Y. (2022) Impact of Nanoparticles on Soil Ecosystems. In The Role of Nanoparticles in Plant Nutrition under Soil Pollution. Sustainable Plant Nutrition in a Changing World; Rajput, V.D., Verma, K.K., Sharma, N., Minkina, T., Eds.; Springer, Cham., Switzerland Baar, Switzerland,. https://doi.org/10.1007/978-3-030-97389-6_3

Salam M., Zheng H.; Liu Y.; Zaib A.; Rehman, S.A.U.; Riaz N.; Eliw M.; Hayat F.; Li H.; Wang F. (2023) Effects of micro(nano)plastics on soil nutrient cycling: State of the knowledge. Journal of Environmental Management, 344, 118437. https://doi.org/10.1016/j.jenvman.2023.118437.

Salem S. S.; Husen A. (2023) Chapter 14 - Effect of engineered nanomaterials on soil microbiomes and their association with crop growth and production. Plant Biology, sustainability and climate change, 311-336. https://doi.org/10.1016/B978-0-323-91933-3.00010-6

Sambangi, P.; Gopalakrishnan, S.; Pebam, M.; Rengan, A.K. (2022) Nano-biofertilizers on soil health, chemistry, and microbial community: benefits and risks. Proc. Indian Natl. Sci. Acad, 88, 357–368. https://doi.org/10.1007/s43538-022-00094-1

Shahane, A.A; Shivay, Y.S. (2021) Soil Health and Its Improvement Through Novel Agronomic and Innovative Approaches. Front. Agron, 6, 3. https://doi.org/10.3389/fagro.2021.680456

Sharma, B.; Tiwari, S.; Kumawat K.C.; Cardinale M. (2023) Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: Potentiality and their limitations. Science of The Total Environment, 860(20), 160476. https://doi.org/10.1016/j.scitotenv.2022.160476.

Singh, B.K.; Yan, ZZ.; Whittaker, M.; Vargas, R.; Abdelfattah, A. (2023) Soil microbiomes must be explicitly included in One Health policy. Nat Microbiol, 8, 1367–1372. https://doi.org/10.1038/s41564-023-01386-y

Singh, R.P.; Handa, R.H.; Manchanda, G. (2021) Nanoparticles in sustainable agriculture: An emerging opportunity. Journal of Controlled Release, 329, 1234-1248. https://doi.org/10.1016/j.jconrel.2020.10.051.

Singh, S.; Prasad, S.M.; Bashri, G. (2023) Fate and toxicity of nanoparticles in aquatic systems. Acta Geochim, 42, 63–76. https://doi.org/10.1007/s11631-022-00572-9

Singh, S.K.; Wu, X.; Shao, C.; Zhang, H. (2022) Microbial enhancement of plant nutrient acquisition. Stress Biology , 2, 3. https://doi.org/10.1007/s44154-021-00027-w

Singh, V.K.; Singh, R.; Kumar, A.; Bhadouria, R. (2021) Effect of Engineered Nanoparticles on Soil Attributes and Potential in Reclamation of Degraded Lands. In Plant-Microbes-Engineered Nano-particles (PM-ENPs) Nexus in Agro-Ecosystems. Advances in Science, Technology & Innovation; Singh, P., Singh, R., Verma, P., Bhadouria, R., Kumar, A., Kaushik, M., Eds.; Springer, Cham., Switzerland Baar, Switzerland,. https://doi.org/10.1007/978-3-030-66956-0_8

Suazo-Hernández, J.; Arancibia-Miranda, N.; Mlih, R.; Cáceres-Jensen, L.; Bolan, N.; Mora, M.d.l.L. (2023) Impact on Some Soil Physical and Chemical Properties Caused by Metal and Metallic Oxide Engineered Nanoparticles: A Review. Nanomaterials, 13, 572. https://doi.org/10.3390/nano13030572

Suman, T.Y.; Pei, D. Nanomaterials Recycling, (2022) Chapter 2 - Nanomaterial waste management. Micro and Nano Technologies, 21-36. https://doi.org/10.1016/B978-0-323-90982-2.00002-0.

Sun, H.; Zhou S.; Jiang, Y.; Xi X., Tan Y.; Zhang, G.; Jiang, N.; Zhou, T.; Yin X.; Wang, M.; Gao, B. (2022) Chapter 7 - Fate and transport of engineered nanoparticles in soils and groundwater. Emerging Contaminants in Soil and Groundwater Systems, 205-25. https://doi.org/10.1016/B978-0-12-824088-5.00003-3.

Sun, W.; Dou, F.; Li, C.; Ma, X.; Ma, L.Q. (2021) Impacts of metallic nanoparticles and transformed products on soil health. Critical Reviews in Environmental Science and Technology, 51(10), 973-1002. https://doi.org/10.1080/10643389.2020.1740546

Sun, Y.; Zhu, G.; Zhao, W.; Jiang, Y.; Wang, Q.; Wang, Q.; Rui, Y.; Zhang, P.; Gao, L. (2022) Engineered Nanomaterials for Improving the Nutritional Quality of Agricultural Products: A Review. Nanomaterials, 12, 4219. https://doi.org/10.3390/nano12234219

Trivedi, M.; Kedari, S.; Nikalje, G.C. (2022) Role of Nanoparticles in Remediation of Contaminated Soil. In The Role of Nanoparticles in Plant Nutrition under Soil Pollution. Sustainable Plant Nutrition in a Changing World; Rajput, V.D., Verma, K.K., Sharma, N., Minkina, T., Eds.; Springer, Cham., Switzerland Baar, Switzerland,. https://doi.org/10.1007/978-3-030-97389-6_15

Trivedi, P.; Leach, J.E.; Tringe, S.G.; Sa, T.; Singh, B.K. (2020) Plant–microbiome interactions: from community assembly to plant health. Nat Rev Microbiol, 18, 607–621. https://doi.org/10.1038/s41579-020-0412-1

Tripathi, G.D.; Javed, Z.; Gattupalli, M., Dashora, K. (2023) Impact of nanomaterials accumulation on the organic carbon associated enzymatic activities in soil. Soil and Sediment Contamination: An International Journal, 32(5), 538-556. https://doi.org/10.1080/15320383.2022.2105813

Ulhassan, Z.; Khan, A.R.; Hamid, Y.; Azhar, W.; Hussain, S., Sheteiwy, M.S.; Salam, A.; Hakeem, K.R.; Zhou, W. (2022) Chapter14 - Interaction of nanoparticles with soil–plant system and their usage in remediation strategies. Metals Metalloids Soil Plant Water Systems, 287-308. https://doi.org/10.1016/B978-0-323-91675-2.00024-X.

Védère C.; Lebrun M.; Honvault N.; Aubertin M.; Girardin C.; Garnier P.; Dignac M.; Houben D.; Rumpel C. (2022) How does soil water status influence the fate of soil organic matter? A review of processes across scales. Earth-Science Reviews, 234, 104214. https://doi.org/10.1016/j.earscirev.2022.104214

Vishwakarma, V.; Ogunkunle, C.O.; Rufai, A.B.; Okunlola, G.O.; Olatunji, O.A.; Jimoh, M.A.(2023) Nanoengineered particles for sustainable crop production: potentials and challenges. 3 Biotech , 13, 163. https://doi.org/10.1007/s13205-023-03588-x

Wagg, C.; Hautier, Y.; Pellkofer, S.; Banerjee, S.; Schmid, B.; van der Heijden, M.G. (2021) Diversity and asynchrony in soil microbial communities stabilizes ecosystem functioning. Elife, 10, e62813. https://doi.org /10.7554/eLife.62813

Wahab, A.; Munir, A.; Saleem, M.H.; AbdulRaheem, M.I.; Aziz, H.; Mfarrej, M.F.B.; Abdi, G. (2023) Interactions of Metal-Based Engineered Nanoparticles with Plants: An Overview of the State of Current Knowledge, Research Progress, and Prospects. J Plant Growth Regul , 42, 5396–5416. https://doi.org/10.1007/s00344-023-10972-7

Wang, Q.; Zhang, P.; Zhao, W.; Noman, S.; Muhammad, A.; Zhu, S.; Sun, Y.; Wang, Q.; Jiang, Y.; Rui, Y. (2023) Effects and the fate of metal-based engineered nanomaterials on soil ecosystem: A review. Pedosphere, in press. https://doi.org/10.1016/j.pedsph.2023.05.004

Wijesooriya, S.N.; Madanayake N.H.; Adassooriya, N.M. (2023) 13 - Impact of nanomaterials on beneficial soil micro-organisms. Nanotechnology in Agriculture and Agroecosystems, 367-385. https://doi.org/10.1016/B978-0-323-99446-0.00006-4.

Wilhelm, R.C.; Amsili, J.P.; Kurtz, K.S.M.; van Es, H.M.; Buckley, D.H. (2023). Ecological insights into soil health according to the genomic traits and environment-wide associations of bacteria in agricultural soils. ISME Communications., 3, 1.

https://doi.org/10.1038/s43705-022-00209-1

Wohlmuth, J.; Tekielska, D.; Čechová, J.; Baránek, M. (2022) Interaction of the Nanoparticles and Plants in Selective Growth Stages-Usual Effects and Resulting Impact on Usage Perspectives. Plants , 11, 2405. https://doi.org/10.3390/plants11182405

Yadav A.; Yadav K.; Abd-Elsalam, K.A. (2023) Exploring the potential of nanofertilizers for a sustainable agriculture. Plant Nano Biology, 5, 100044. https://doi.org/10.1016/j.plana.2023.100044

Zhang, P.; Guo, Z.; Ullah, S.; Melagraki, G.; Afantitis, A.; Lynch, I. (2021) Nanotechnology and artificial intelligence to enable sustainable and precision agriculture. Nat. Plants , 7, 864–876. https://doi.org/10.1038/s41477-021-00946-6

Zhang, Y.W.; Wang, K.B.; Wang, J.; Liu, C.; Shangguan, Z. (2021) Changes in soil water holding capacity and water availability following vegetation restoration on the Chinese Loess Plateau. Sci Rep, 11, 9692. https://doi.org/10.1038/s41598-021-88914-0

Zheng, W.; Cui, T.; Li, H. (2022) Combined technologies for the remediation of soils contaminated by organic pollutants. A review. Environ Chem Lett , 20, 2043–2062. https://doi.org/10.1007/s10311-022-01407-y

Zhou, M.; Liu, C.; Wang, J.; Meng, O.; Yuan, Y.; Ma, X.; Liu, X.; Zhu, Y.; Ding, G.; Zhang, J.; Zeng, X.; Du, W. (2020) Soil aggregates stability and storage of soil organic carbon respond to cropping systems on Black Soils of Northeast China. Sci Rep, 10, 265. https://doi.org/10.1038/s41598-019-57193-1

Zhou, P.; Adeel, M.; Shakoor, N.; Guo, M.; Hao, Y.; Azeem, I.; Li, M.; Liu, M.; Rui, Y. (2021) Application of Nanoparticles Alleviates Heavy Metals Stress and Promotes Plant Growth: An Overview. Nanomaterials , 11, 26. https://doi.org/10.3390/nano11010026

Zhu, Y.; Peng, J.; Chen, C.; Xiong, C.; Li, S.; Ge, A.; Wang, A.; Liesack, W. (2023) Harnessing biological nitrogen fixation in plant leaves. Trends in Plant Science, 28(12), 1391-1405. https://doi.org/10.1016/j.tplants.2023.05.009

Zhu,P.; Yang, S.; Wu, Y.; Ru, Y.; Yu, X.; Wang, L.; Guo, W. (2022) Shifts in Soil Microbial Community Composition, Function, and Co-occurrence Network of Phragmites australis in the Yellow River Delta. Front. Microbiol., Sec. Terrestrial Microbiology, 13. https://doi.org/10.3389/fmicb.2022.858125.

Wu, L.; Zhang, Y.; Guo, X.; Ning, D.; Zhou, X.; Feng, J.; Yuan, M.M.; Liu, S.; Guo, J.; Gao, Z.; MA, J.; Kuang, J.; Jian, S.; Han, S.; Yang, Z.; Ouyang, Y.; Fu, Y.; Xiao, N.; Liu, X.; Wu, L.; Zhou, A.; Yang, Y.; Tiedje, J.M.; Zhou, J.(2022) Reduction of microbial diversity in grassland soil is driven by long-term climate warming. Nat Microbiol, 7, 1054–1062. https://doi.org/10.1038/s41564-022-01147-3

Wu, S., Konhauser, K.O., Chen, B. et al. (2023) "Reactive Mineral Sink" drives soil organic matter dynamics and stabilization. npj Mater. Sustain. 1, 3. https://doi.org/10.1038/s44296-023-00003-7

Wurst, S.; Sonnemann, I.; Zaller, J.G. (2018) Soil Macro-Invertebrates: Their Impact on Plants and Associated Aboveground Communities in Temperate Regions. In Aboveground–Belowground Community Ecology. Ecological Studies; Ohgushi, T., Wurst, S., Johnson, S., Eds.; Springer, Cham., Switzerland Baar, Switzerland,; vol 234. https://doi.org/10.1007/978-3-319-91614-9_8

Yu S.; Liu J.; Yin Y.; Shen, M. (2018) Interactions between engineered nanoparticles and dissolved organic matter: A review on mechanisms and environmental effects. Journal of Environmental Sciences, 63, 198-217. https://doi.org/10.1016/j.jes.2017.06.021.