**Role of Nanoparticles in Perturbation of Soil Microbial Communities**

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**Abstract**

Agriculture faces numerous challenges, including reduced crop yield, nutrient deficiencies, and decreased soil organic content. Conventional fertilizers are applied to address these issues, but their nutrient release often does not align with the plant's needs, resulting in low nutrient use efficiency [1, 2]. Nanotechnology offers a promising solution through the development of nanoparticles (NPs) and nanodevices for agricultural applications. Nanofertilizers release nutrients in a controlled manner, leading to higher crop growth and reduced nutrient loss compared to chemical fertilizers [3]. However, the introduction of NPs into soil raises concerns about their impact on microbial communities and soil properties. NPs can interact positively and negatively with plants and rhizospheric communities, affecting soil properties and the environment [4, 5]. The presence of NPs in soil can lead to hazardous environmental effects and may alter soil microflora through toxicities or changes in toxin bioavailability. Microbial communities play a critical role in agricultural productivity, and understanding the impact of NPs on beneficial bacteria is crucial. NPs can induce ROS production, leading to cell damage and microbial biomass reduction [6]. Comprehensive technology, public awareness, and integrated legislation are essential for regulating NPs and preventing their toxicity [7]. In conclusion, NPs offer significant agricultural improvements, but their potential adverse effects on the environment and microbial communities should be considered. Implementing sustainable soil management practices and evaluating NP fate through modern approaches can help minimize environmental damage and promote responsible nanofertilizer use in agriculture.

**Key words:** Microbial communities, nanoparticles, nanofertilizer, agriculture, sustainability

**Introduction**

Agriculture globally faces various challenges, including reduced crop yield, diminished nutrient absorption, decreased soil organic content, and multi-nutrient deficiencies. To address these deficiencies, fertilizers are supplemented to enhance crop production and fulfill the plant's nutrient requirements. However, the release of nutrients from fertilizers should align with the plant's needs. Unfortunately, the actual amount of nutrients reaching the crop's target site is often insufficient due to factors like leaching, hydrolysis, photolysis, decomposition, insolubility in soil, or immobilization by microorganisms [2]. It resulted in low efficiency, as evident from the low nutrient use efficiency (NUE) of nitrogen, phosphorus, and potassium, as NUE values for these macronutrients are approximately 30-35%, 18-20%, and 35-40%, respectively [1]. Consequently, a significant portion of applied fertilizers remains inaccessible [2].

The field of nanotechnology is being explored as a new source of key improvements in the agricultural sector as it enables the development of nanoparticles (NPs) and nanodevices for applications in plant biotechnology and agriculture [8]. NPs release nutrients in a controlled manner, reducing loss and improving crop growth and requires in lower nutrient quantities as compared to chemical fertilizers [3]. Slow-release nano-fertilizers increase grain yield and minimize nutrient leaching. Nano urea-hydroxyapatite (HA) binds strongly to urea, extending release time by ~12 times while releasing nitrogen over 60 days, while commercial fertilizers do so in four days [9]. Nanofertilizers enhance plant biomass, yield, and essential amino acid production [3]. The supplementation of NPs into soils for eventually ends up raising concerns against microbial communities. The NPs possess positive and negative associations with plants and rhizospheric communities. It is quite evident that NPs within the soil can go belowground to hamper soil properties and cause hazardous effect on the environment [4, 5]. They have been known to cause colossal hindrances towards soil microflora either through toxicities or altering the bioavailability of toxins [8, 10].

Soil microorganisms play a crucial role in agricultural productivity by recycling elements, decomposing organic matter, and directly promoting plant growth through various mechanisms. They also indirectly enhance plant growth by suppressing plant pathogens and commonly used as soil inoculants to boost agricultural. Therefore, understanding the impact of engineered nanoparticles on these beneficial bacteria is essential [4,5]. The impact of nanoparticles on microorganisms in soil and other environmental niches needs further investigation, considering their wide range of applications. Changes in bacterial community structure indicate that nanoparticles can potentially modify soil microbiomes. However, the specific effects are influenced by the composition of the nanoparticles, emphasizing the need to assess the environmental impacts of different nanoparticle formulations. Therefore, it is crucial to understand how NPs affect crop performance and evaluate the diversity of soil bacterial communities when exposed to specific metal oxide nanoparticles. This chapter provide insight on the fate and behaviour of NPs within soils

**Source of nanoparticles in agriculture**

NPs are ubiquitous entities and can originate from natural or human sources. NPs in the air are called ultrafine particles, while those in water and soil are colloids with varying sizes. Naturally occurring NPs have been present since the earth's formation and are found extensively in the atmosphere, oceans, soil, water, and living organisms. Out of all ecosystems (soil, water and air), soil is believed to receive the highest levels of NPs from various sources, including engineered NPs introduced through sewage and faulty agricultural practices [10]. Understanding the impact of NPs on soil enzymatic activities and the environment is crucial.

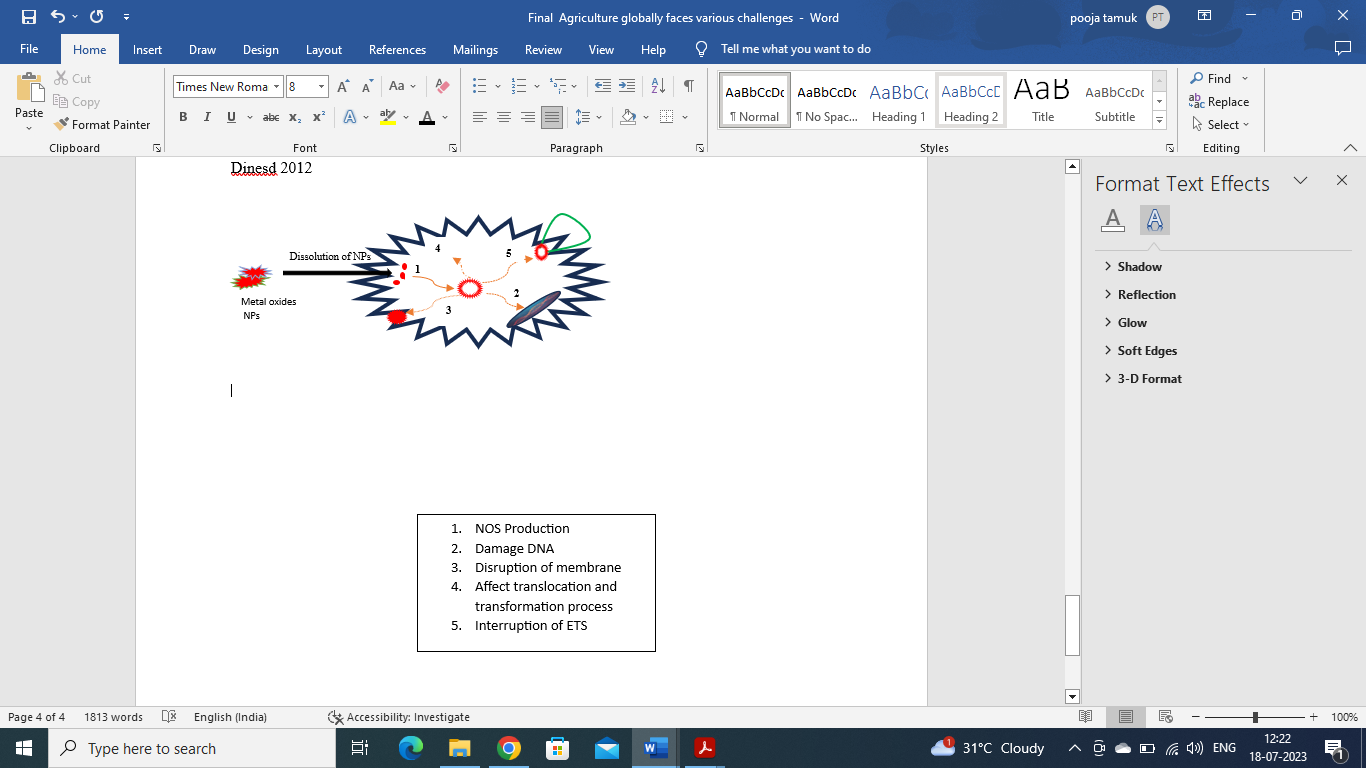
In agriculture, nanofertilizers are a significant source of NPs, offering a promising approach to enhance productivity. Nanotechnology has the potential to genetically improve plants and drugs at the cellular level, while increasing the efficiency of conventional fertilizers [3]. Nanofertilizers with their large surface area can release nutrients slowly, matching crop requirements and improving nutrient uptake efficiency by threefold [11], thereby reducing water pollution [3]. Silver and zinc oxide NPs have been reported to exhibit anti-phytopathogenic activity, enhance seed germination, and promote plant growth. With zinc-deficient soils in India, nanoparticulate zinc formulations can be utilized [12].

NPs can potentially impact the physicochemical properties of soil and microbial metabolic activities in rhizospheric soils. However, the small size and mobility of NPs (10 nm) can lead to unintended cellular effects and potential toxicity when taken up by soil organisms [4]. The form and concentration of NPs play a crucial role in determining their transport, bioavailability, toxicity, and ecological impact. Hence, examining the role of nanoscale contaminants is important in current and future pollution scenarios in soil and aquatic ecosystems [5, 13]. NPs can significantly impede soil microflora through direct toxicity or by altering toxin bioavailability, and they can also indirectly disrupt organic compound synthesis and create antagonistic interactions. Various factors, such as physicochemistry, concentration, time, and growth medium, influence the impact of NPs on microbial communities [8, 10].

**Effect of nanoparticles on soil microbe**

When NPs are applied to soil, they can persist in sediment for an extended period, and their interaction with soil and metal ion release is influenced by soil properties and the aging process [5]. Water present in the soil can dissolve NPs, resulting in increased bioavailability and uptake of the released metal ions. The dissolution of NPs is influenced by factors such as soil type, texture, physicochemical properties, and mode of application. Consequently, the soil microbiome is exposed to emerging contaminants like metal-engineered nanoparticles, which can affect enzymes and microorganisms involved in soil processes. Enzymes and microorganisms involved in soil processes can be affected by NPs, leading to reduced microbial activity [8, 9].

Application of zero-valent NPs (nZVI) with straw amendment has been found to reduce microbial biomass, indicating bactericidal effects on microbial functional groups [14]. Oxidation of nZVI can result in the production of reactive oxygen species [ROS] in living cells, leading to membrane disruption, leakage of intracellular materials, and impairment of biochemical processes, ultimately causing cell death [Figure 1]. The accumulation of ROS due to NPs can reduce crop productivity by affecting seed germination and root elongation, potentially posing risks to human health [6, 8]. Nanomaterials such as CuO and Fe3O4 have been shown to alter soil microbial populations and their toxicity is related to their solubility and bioavailability [15]. The presence of ZnO NPs has been found to decrease extractable soil DNA and the activities of soil protease, catalase, and peroxidase [16]. The application of single-walled carbon nanotubes (SWCNTs) in soil has been shown to decrease the activities of various enzymes involved in organic matter degradation, potentially due to the generation of ROS and physical damage to microbial cells [8, 17]. C60 fullerenes have been found to decrease the number of fast-growing bacteria in soil, while respiration and microbial biomass were unaffected [18].



1. NOS Production
2. Damage DNA
3. Disruption of membrane
4. Affect translocation and transformation process
5. Interruption of ETS

Figure 1. The possible ways of damaging the bacterial cell by NPs.

Studies have shown that the introduction of CuO NPs in water-logged paddy soils caused a decline in microbial biomass, and ZnO, TiO2, CeO2, and Fe3O4 NPs have been found to alter soil bacteria and nitrogen fixation processes [19]. ZnO and CeO2 NPs can reduce the abundance of specific bacteria involved in phosphorus and potassium solubilization, as well as negatively affecting their enzyme activities [19]. The toxic effects of ZnO NPs on the ammonification process in soil have been observed, with time-dependent and dose-dependent responses, particularly in acidic soils [20]. Furthermore, concentration levels of NPs have a critical role in microbial interactions. It has been speculated that NPs-toxicity on soil microbes is directly proportional to their low concentration levels as assessed on mycorrhizal fungi, tomato and maize plant-interactions in response to ZnONPs [21].

**Mitigation approaches for NP-toxicity in environment**

It is intricate to deduce the toxicity of NPs within the ecosystem, subsequently. Due to inadequate detection and monitoring devices, NP-interaction within the environment was neglected, but now various tools elucidating the fate of NPs in the environment are being focused. Different biomarkers are useful for tracking NPs within the environment. Therefore, serve as the most crucial biological assessment tool. In addition, an idea of permeable-ion barriers has also been formulated to arrest NPs [22]. A complete form of advanced and comprehensive technology comprising of public awareness and integrated legislation is a substantial and proactive approach to regulate the intricacy of NPs to prevent their toxicity [7]. Further, to consider ecotoxicology and NP fate within the environment, development of various regulatory actions and environmental testing and monitoring would provide validated results [**23**]. Therefore, these assessments are required to be modulated with contemporary approaches to give accurate results to avert NP-mediated environmental damage.

The toxicity of NPs in the ecosystem is complex, but advancements in detection and monitoring tools have shed light on their fate in the environment. Biomarkers and permeable-ion barriers are valuable for tracking and containing NPs [22]. Comprehensive technology, public awareness, and integrated legislation are proactive approaches to regulate NPs and prevent their toxicity [7]. Regulatory actions, environmental testing, and monitoring are necessary for accurate assessment of ecotoxicology and NP fate [23]. These contemporary approaches are essential to mitigate NP-induced environmental damage.

**Conclusions**

NPs have the potential to stimulate plant growth and control pollution, but they also pose a serious threat to the environment and rhizospheric populations due to their accumulation potential. Due to their dual actions, it is crucial to gather valuable information about NPs and their impact on biological interactions in the soil. The extensive production and persistence of nano-products in the soil ecosystem have disrupted beneficial microflora and soil components. The unique properties of NPs, such as surface charges, size, area, and reactivity, hinder positive interactions among soil, plants, and microbes. The proliferation of NPs in the soil can negatively affect microflora, leading to toxicity, accumulation, and resistance mechanisms. To address these challenges, it is crucial to gather valuable information about NPs and their impact on the soil ecosystem. Regulatory actions, environmental testing, and monitoring are essential for accurately assessing the ecotoxicology and fate of NPs. By implementing contemporary approaches, we can mitigate the potential environmental damage caused by NPs and safeguard the long-term health of our ecosystems. It is crucial to prioritize sustainable practices and responsible use of NPs to strike a balance between their benefits and potential risks.

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