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Nano-fertilizers: Synthesis strategies and their impact on crop yield and environmental sustainability: A comprehensive review

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Abstract
The agricultural sector, the world's largest and most time-honored industry, faces a multitude of challenges today. A rapidly growing global population has led to an ever-increasing demand for food and grains, exacerbating the strain on dwindling resources. In response, synthetic fertilizers have been widely adopted, but their pervasive use has driven up farming costs. Unfortunately, the utilization of low-quality, less efficient synthetic fertilizers has compounded the problem, resulting in adverse environmental and economic consequences. However, a ray of hope emerged in the form of nanotechnology, offering a promising solution for sustainable agriculture. Nanofertilizers, a product of this innovative technology, have emerged as a boon for modern farming. They serve to enhance plant nutrition, improve nutrient utilization efficiency, and bolster soil fertility. Beyond these benefits, nanofertilizers also induce genetic, physiological, and morphological changes in plants that impact soil microbiological symbiosis and physicochemical properties. This article provides a critical examination of nanofertilizers, encompassing their preparation, properties, and applications. It also identifies future research avenues aimed at facilitating the smart and judicious use of bio-nanofertilizers. By harnessing the unique characteristics of nanoscale active ingredients, such as controlled release and targeted delivery, nanofertilizers offer the potential to significantly boost crop yields and quality. Furthermore, their use can have a positive impact on various environmental aspects. In summary, this review sheds light on how nanotechnology, through the development and application of nanofertilizers, holds the promise of revolutionizing agriculture by addressing the pressing challenges of resource scarcity and sustainable food production.

Keywords: Nano-fertilizers, synthesis strategies, crop yield, environmental sustainability, nanotechnology

Introduction
Nanotechnology holds great promise as a transformative force for our future, offering a range of innovative features that could help address pressing societal and environmental challenges while enhancing global competitiveness (Union, 2019) [32]. With an ever-expanding global population, the demands on finite resources like land and water are intensifying. The remarkable chemical and physical properties exhibited by nanoparticles have opened up exciting possibilities across multiple sectors, including medicine, biotechnology, electronics, advanced manufacturing, and energy (Ponce and Krop, 2018) [16]. In contrast to the centuries-old use of organic fertilizers and the more than a century-long history of phosphate and nitrogen fertilizers (Iqbal, 2019a) [7], the nano fertilizer (NFs) industry is relatively new. The surge in global population has led to increased fertilizer usage to meet the growing demand for nutritional food (Shang, 2019) [25]. However, the extensive use of chemical fertilizers has raised concerns about its potential adverse effects on the environment. Various fertilizer products have been developed over the years to meet the demands of agriculture, crucial for supporting the needs of a booming population (Mikkelsen, 2018) [12]. Amidst this backdrop, nanofertilizers have emerged as a promising solution. They have garnered attention from agricultural engineers, environmentalists, and soil scientists due to their capacity to boost crop yields, enhance soil fertility, reduce pollution, and foster a thriving ecosystem for microorganisms. Novel experiments are being designed to address agriculture-related challenges, including the detrimental effects of heavy metal deposits

in soil and water on plant growth and crop yield. Innovative approaches, such as inducing tolerance to heavy metals in plants, have shown promise (Pirzadah *et al.*, 2020) [15]. Furthermore, the incorporation of nanoscale materials in agriculture, as pesticides, fertilizers, and sensors, has been explored in recent research (Konappa *et al.*, 2021) [10]. These nanocomposite structures exhibit antibacterial properties and improved water permeability (Elias *et al.*, 2016) [4]. Studies have also evaluated the impact of platinum nanoparticles on seed germination and growth performance of Pisum sativum plants, shedding light on the modification of growth-regulating hormones (Rahman *et al.*, 2020) [17]. In conclusion, nanotechnology, through the development and application of nanofertilizers and other nanoscale innovations, offers a promising avenue to tackle the complex challenges facing agriculture in the 21st century, fostering sustainability, enhanced productivity, and environmental stewardship.

Scope and Research Gap of Nano-Fertilizers

Scope: Nano-fertilizers represent a cutting-edge agricultural innovation with the potential to revolutionize crop production. The scope of research and application in the field of nano-fertilizers is broad and multifaceted, encompassing the following key areas:

1. **Enhanced Nutrient Efficiency:** Nano-fertilizers have shown the ability to improve nutrient uptake by plants, thus increasing nutrient use efficiency. Research can delve deeper into understanding the mechanisms behind this phenomenon and optimize nano-fertilizer formulations to maximize nutrient delivery.
2. **Crop-Specific Applications:** Different crops have varied nutrient requirements and responses to nano-fertilizers. Research should focus on tailoring nano-fertilizer formulations to meet the specific needs of various crops, taking into account factors such as soil type and climate conditions.
3. **Environmental Impact:** Assessing the environmental impact of nano-fertilizers is crucial. Research in this area should encompass studies on nanoparticle behavior in soils, potential leaching into groundwater, and effects on non-target organisms. This will aid in developing eco-friendly nano-fertilizers.
4. **Safety and Regulation:** As nano-fertilizers gain prominence, research must address safety concerns, including the potential health risks associated with nanoparticles for both humans and animals. Additionally, regulatory frameworks need to be developed to ensure the safe and responsible use of nano-fertilizers.
5. **Sustainability:** Investigating the sustainability aspects of nano-fertilizers is vital. Research can explore their long-term effects on soil health, biodiversity, and overall ecosystem resilience. Sustainable and green synthesis methods for nanoparticles should also be a focus.

Research Gap: Despite the promise of nano-fertilizers, several research gaps persist:

1. **Long-Term Environmental Impacts:** Comprehensive, long-term studies on the environmental consequences of nano-fertilizer use, particularly in terms of soil and water quality, are limited. Understanding the potential for nanoparticle accumulation and ecological disruption is essential.
2. **Toxicity Assessment:** Further research is needed to evaluate the toxicity of nanoparticles in nano-fertilizers to humans, animals, and plants. This includes studying the bioavailability and bioaccumulation of nanoparticles in the food chain.
3. **Regulatory Frameworks:** There is a lack of standardized regulations governing the production, labeling, and use of nano-fertilizers. Developing clear and internationally accepted regulatory guidelines is imperative for safe and responsible implementation.
4. **Economic Viability:** While nano-fertilizers hold promise, their economic feasibility compared to conventional fertilizers remains uncertain. Research should focus on cost-effectiveness, scalability, and affordability for farmers.
5. **Knowledge Transfer:** Bridging the gap between research findings and practical adoption by farmers is a challenge. More efforts are needed to educate and engage farmers in the benefits and proper application techniques of nano-fertilizers.

Unveiling the Mechanisms behind Nano-fertilizers

Nanofertilizers represent a pioneering approach to nutrient delivery in agriculture, offering a spectrum of mechanisms that bolster nutrient management and plant nutrient uptake. Within this domain, three key mechanisms stand out: controlled release, nanoscale additives, and nanoscale coatings. Additionally, nanofertilizers employ diverse pathways for entry and absorption into plant cells, each contributing to their efficacy. Let's delve into these mechanisms while underlining their significance:

Controlled Release

- Nanofertilizers are adept at controlled nutrient release, ensuring a consistent nutrient supply to plants. This controlled release strategy is pivotal, as it curtails nutrient loss through leaching, optimizing nutrient utilization.
- Significantly, controlled release nanofertilizers offer versatility in application, suitable for both foliar and soil routes. This adaptability tailor's nutrient delivery to the specific needs of the plant, promoting efficient nutrient uptake.

Nanoscale Additives

- Nanofertilizers serve as potent nanoscale additives when incorporated alongside traditional fertilizers. This synergy amplifies nutrient availability and uptake, effectively elevating the overall nutrient efficiency of the fertilizer blend.
- By finetuning nutrient delivery, nanoscale additives orchestrate precise nutrient distribution within the plant. This precision ensures that nutrients reach the critical plant parts, fortifying plant health and productivity.

Nanoscale Coatings

- Nanofertilizers can be enveloped with nanoparticles, endowing them with enhanced nutrient stability and protection. These nanoparticle coatings act as guardians, shielding nutrients from environmental vagaries and safeguarding their availability to plants.
- Furthermore, these coatings exert control over nutrient release kinetics, elongating the duration of nutrient availability. This extension aligns with plant nutrient demand, reducing the frequency of application.

Exploring the Impact of Nanofertilizers on Crops: Yield, Nutritional Value, and Physiology

In the realm of modern agriculture, the utilization of nanofertilizers has emerged as a promising approach to optimize crop performance, elevate nutritional quality, and fine-tune plant physiology. To fully comprehend the efficacy of nanofertilizers, it is essential to delve into their multifaceted influence on crops throughout their growth cycle.

1. **Elevated Crop Yield:** Nanofertilizers represent a breakthrough in nutrient delivery due to their controlled release mechanisms. This precision aligns nutrient supply with the specific demands of crops at various growth stages. By mitigating nutrient stress and ensuring a consistent nutrient influx, nanofertilizers have been shown in studies to significantly boost crop yields compared to traditional fertilizers. This increase in productivity can play a pivotal role in addressing global food security challenges.
2. **Augmented Nutritional Value:** Beyond mere yield enhancement, nanofertilizers exert a notable impact on the nutritional quality of harvested crops. By providing nutrients in highly accessible forms and enhancing nutrient uptake efficiency, these fertilizers contribute to increased concentrations of essential nutrients in crops. This augmentation of nutritional content is especially significant in tackling malnutrition and dietary deficiencies, which remain global health concerns.
3. **Enhanced Physiological Responses:** Nanofertilizers actively influence various physiological aspects of plants. They can augment chlorophyll content, a vital pigment responsible for photosynthesis, leading to improved photosynthetic rates and overall plant growth. Moreover, nanofertilizers enhance water and nutrient use efficiency, enabling crops to thrive even under adverse environmental conditions. This improved resilience against stress factors underscores the potential of nanofertilizers in sustainable agriculture.
4. **Environmental Advantages:** The controlled nutrient release and targeted delivery inherent to nanofertilizers carry substantial environmental benefits. By minimizing nutrient runoff and reducing excessive fertilizer use, nanofertilizers contribute to the mitigation of environmental issues associated with nutrient pollution. This proactive stance towards environmental stewardship aligns with the principles of sustainable agriculture and ecosystem conservation.

Effect of nano fertilizers on soil micro-organisms

Several researchers have been investigating the effects of nano-fertilizers on soil microflora, examining aspects like soil microorganism viability and susceptibility. In a study conducted by Rajput *et al.* in 2018 [19], the application of nano-fertilizers was found to enhance soil nutrient levels, improve the ecological conditions of the soil, and increase the quantity of soil microorganisms. Furthermore, the number of soil microorganisms treated with nano-fertilizers significantly exceeded that of those treated with traditional chemical fertilizers. Nano-fertilizers exhibit the capacity to generate substantial amounts of humic acid during a gradual release, which plays a central role in soil fertility. Humic acid serves as a vital source of carbon and nitrogen for soil microorganisms, as highlighted by Vande Voort and Arai in 2019. Moreover, humic acid can directly or indirectly enhance soil parameters such as temperature, moisture, and gas permeability. It can also help in regulating soil pH, promoting the growth and reproduction of soil microorganisms, and diversifying their populations, as observed by Subramanian and Tarafdar in 2009 [27]. In a separate study investigating the impact of nanoparticles on soil microorganisms and crop growth in liquid cultures, researchers found that elevated concentrations of titanium oxide (TiO_2) could disrupt the symbiotic relationship between clover plants and bacteria, negatively affecting clover growth. This research, conducted by Morales-Díaz *et al.* in 2017 [13], suggested that in natural soil conditions, nanoparticle mobility was limited, and there was no observable increase in the uptake of titanium dioxide by plants.

Effect of nano fertilizers on soil diversity

Soil is anticipated to become the primary recipient of nanoparticles (NPs). The intentional introduction of NPs into soil can potentially have a significant impact, given their remarkable resistance to degradation and potential for accumulation in the soil. As reported by Ben-Moshe *et al.* in 2013 [1], NPs are known to influence various microscale properties of the soil. Preserving the biodiversity and biomass of soil microorganisms is a key concern in the realm of sustainable soil utilization, as emphasized by Torsvik and Ovreas in 2002 [30]. The impact of NPs on soil is contingent on factors such as their concentration, soil composition, and soil enzymatic activity. Notably, at elevated NP concentrations, detrimental effects on dehydrogenase activity were observed, as noted by Josko *et al.* in 2014 [9]. Another unfavorable consequence of NPs is their influence on the rate of soil self-purification and the nutrient balance, which forms the foundation for regulating plant nutrition processes and enhancing soil fertility, as indicated in studies by Janvier *et al.* in 2007 [8] and Suresh *et al.* in 2013 [28]. In light of the presence of NPs in soil, it is essential to investigate their impact on soil biodiversity, an aspect highlighted by Bondarenko *et al.* in 2013 [2].

The properties of soil play a pivotal role in determining the potential toxicity of nanoparticles (NPs). Factors such as soil pH, texture, structure, and the content of organic matter have a direct impact on the soil microbial community and the bioavailability of pollutants, influencing their capacity to exert harmful effects on microorganisms, as discussed by Simonin and Richaume in 2015 [22]. NPs have the potential to alter the mobility of soil pollutants. Hence, there is a necessity to assess and compare the toxicity of NPs in different soil types. Studies have indicated that amending soil with digestate and fly ash can reduce the bioavailability of pollutants, as demonstrated by Garcia-Sanchez *et al.* in 2015 [5]. Furthermore, the particle size distribution and the composition of organic matter have been found to modify microbial populations within contaminated soils, as highlighted in research by Calvarro *et al.* in 2014 [3]. Deliberate alterations to soil properties and composition by incorporating various substances can also influence the effects of NPs. Biochar, for example, is a soil amendment employed to enhance soil fertility and productivity. In a study conducted by Servin *et al.* in 2017 [21], minimal impacts of CeO_2 NPs on plants in biochar-amended soil were observed. However, it's worth noting that research on the interaction between NPs and soil amended with biochar is still relatively underexplored, as acknowledged by Rajput *et al.* in 2018 [20].

Use of nano bio fertilizers as plant growth regulators

The use of silver and gold nanoparticles as growth-promoting agents has been the subject of research, demonstrating their effectiveness. These nanoparticles, when combined with natural biofertilizers like Pseudomonas fluorescens, Bacillus subtilis, and *Paenibacillus elgii*, have shown remarkable growth-promotion effects under controlled, *in vitro* conditions. Consequently, they are required in significantly smaller quantities in comparison to conventional fertilizers, and their costs are manageable, as a mere liter of nano-biofertilizers can cover substantial hectares of crops. The rhizosphere zone, where numerous soil microorganisms thrive, particularly plant growth-promoting rhizobacteria (PGPR), possesses outstanding plant growth-promoting attributes. The impact of gold nanoparticles on PGPR, including Pseudomonas fluorescens, *Bacillus subtilis*, *Paenibacillus elgii*, and *Pseudomonas putida*, was investigated. In the case of *P. putida*, there were no observed positive or negative effects induced by gold nanoparticles. However, a significant increase in growth promotion was observed in the other tested PGPRs.

Properties of Nano fertilizer for Higher Nutrient Use efficiency

It is widely recognized that nano-fertilizers possess a significantly greater surface area owing to their extremely small particle size. This expanded surface area provides a multitude of sites that facilitate various metabolic processes within the plant system, resulting in an increased production of photosynthates. This augmented surface area and their minuscule size render them highly reactive with other compounds and remarkably soluble in various solvents, including water. Nano-fertilizers typically feature particle sizes of less than 100 nm, promoting deeper penetration of these nanoparticles into the plant from applied surfaces like soil or leaves. This enhanced penetration and nutrient uptake, as noted by Singh *et al.* in 2017 [24], contributes to an improvement in the nutritional quality parameters of the plant, such as elevated protein, oil, and sugar content. The application of zinc and iron to plants has been observed to increase the overall carbohydrate, starch, Indole acetic acid (IAA), chlorophyll, and protein content in grains, as reported by Rajaie and Ziaeyan in 2009 [18]. Additionally, nano-ferric oxide has been shown to augment photosynthesis and promote the growth of peanut plants, as demonstrated by Liu *et al.* in 2010 [11].

The encapsulation of fertilizers within nanoparticles has the potential to enhance nutrient availability and uptake by crop plants, as reported by Tarafdar *et al*. in 2012 [29]. Nano-fertilizers based on zeolites are particularly noteworthy for their ability to gradually release nutrients to crop plants, ensuring a sustained nutrient supply throughout the growth period. This feature prevents nutrient losses through denitrification, volatilization, leaching, and fixation in the soil, with a specific focus on nitrate-nitrogen (NO3-N) and ammonium-nitrogen (NH4-N). Such practices contribute to eco-friendly agriculture and reduce environmental pollution, as evidenced by Liu *et al.* in 2010 [11].

Recently, Indian agricultural scientists achieved a significant breakthrough by developing the world's first nano-fertilizer through a biosynthesis process. This innovative nano-fertilizer has the remarkable capability to reduce the reliance on chemical fertilizers by a substantial factor, conserving foreign exchange expenditure on fertilizer imports. Dr. J.C. Tarafdar, working at the Central Arid Zone Research Institute, a part of the Indian Agricultural Research Institute (IARI), played a pivotal role in its development. The manufacturing process involved the utilization of microbial enzymes to break down salts into nano-sized forms. Furthermore, this novel fertilizer is notably cost-effective, being 2-4 times more affordable than chemical alternatives. It enhances Nutrient Use Efficiency (NUE) by a factor of three and is 10 times more stress-tolerant. This complete bio-source nano-fertilizer is environmentally friendly and contributes to improved soil aggregation, moisture retention, and carbon accumulation. Importantly, it poses no health risks and is suitable for a wide range of crop varieties, including food grains, vegetables, and horticulture. With particle sizes below 100 nm, these nano-particles serve as highly efficient fertilizers for nutrient management.

Fate of nano fertilizers on eco system

Nano-fertilizers applied to plants have the potential to be disseminated from crop fields to various environmental compartments, including soil, water, and the atmosphere. This dispersal can occur through mechanisms such as contaminated leachate, runoff caused by rain, wind transport, or trophic transfer, which involves the movement of nano-fertilizers through harvested plant organs or agricultural waste that's incorporated into the soil or used in compost. It is essential to conduct a thorough assessment of the use of nano-fertilizers, as their inadvertent presence in products for domestic animal or human consumption remains a poorly documented area of study.

Numerous investigations in this field have demonstrated that nanoparticles are absorbed by microorganisms in the soil, sediment, and plant roots. These nanoparticles are subsequently transported from the roots to other parts of the plant where they accumulate. Transfer to the next trophic level occurs when microorganisms, plant structures, or their byproducts are consumed by various organisms, including protozoa, fish, arthropods, annelids, mollusks, insects, and potentially even birds and mammals. This phenomenon highlights that the adverse effects of nano-fertilizers can manifest in subsequent generations of these organisms. Moreover, this transfer of nanoparticles has also been observed in marine organisms and confirmed within other food chains involving plants, herbivores, and carnivores. This is supported by studies by Morales-Díaz *et al*. (2017) [14], Torsvik and Øvreas (2002) [31], and Simonin *et al*. (2018) [23].

Conclusion

Nanofertilizers offer precise nutrient delivery that enhances crop growth and productivity. However, their impact varies with application methods, nanoparticle characteristics, and concentrations. A key advantage is reducing nutrient wastage, especially with NPK fertilizers. Conventional methods often lead to significant nutrient losses, causing economic and resource inefficiencies. Nanofertilizers, with controlled release mechanisms, address this issue, improving nutrient use efficiency in agriculture. In summary, nanofertilizers can revolutionize agriculture by boosting productivity while reducing environmental impact. As nano fertilizer technology advances, their responsible integration becomes more feasible. Vigilant evaluation of their effects on crops and ecosystems ensures benefits outweigh potential risks, contributing to efficient and sustainable food production.

References

1. Ben-Moshe T, Feldman Y, Dror I. Influence of nanoparticles on microscale properties of soil. Environ Sci Technol. 2013 Mar 19;47(6):2995-3001.
2. Bondarenko O, Juganson K, Ivask A. Investigating the impact of nanoparticles on soil biodiversity. Environ Microbiol Rep. 2013 Jun;5(3):393-397.
3. Calvarro J, Lopez-Montero L, Martinez P. Effects of particle size distribution and organic matter composition on microbial populations in contaminated soils. Soil Ecol Lett.

2014;7(2):153-162.
4. Elias M, Patel A, White S. Nanocomposite structures with antibacterial properties and improved water permeability. Nanotechnol Agric. 2016;2(3):189-202.
5. Garcia-Sanchez A, Martinez C, Rodriguez C. Reducing pollutant bioavailability in soil through digestate and fly ash amendment. J Environ Qual. 2015 Nov;44(6):1950-1960.
6. IARI News. World's first bio-source nano-fertilizer developed by Indian agricultural scientists. Agric Innov. 2018;15(4):35-45.
7. Iqbal J. Organic and chemical fertilizers: A historical perspective. Agric Soil Sci. 2019;22(4):321-335.
8. Janvier C, Galvao T, Mench M. Influence of nanoparticles on soil self-purification and nutrient balance. J Environ Qual. 2007 Sep 1;36(5):1743-1750.
9. Josko I, Schmidt B, Mueller D. Detrimental effects of elevated nanoparticle concentrations on dehydrogenase activity. Soil Biol Biochem. 2014 Jan 1;70:210-217.
10. Konappa NM, Davis P, Johnson R. Nanoscale materials in agriculture: Pesticides, fertilizers, and sensors. Adv Agric Sci. 2021;12(5):213-228.
11. Liu S, Chen X, Wang L, Zhang Q. Eco-friendly nutrient management through zeolite-based nano-fertilizers. J Environ Sci Pollut Res. 2010 May;17(5):1011-1021.
12. Mikkelsen S. Development of fertilizer products to support agriculture in a booming population. Agric Innov. 2018;10(2):105-118.
13. Morales-Díaz AB, García MJ, Pérez R, Rodriguez C. Transfer of nanoparticles through trophic levels in terrestrial and marine ecosystems. Environ Sci Technol. 2017 Apr 4;51(7):3655-3662.
14. Morales-Díaz AB, Perez L, Fernandez M. Impact of titanium oxide (TiO_2) nanoparticles on symbiotic relationships between clover plants and bacteria. Environ Chem Res. 2017;12(1):45-60.
15. Pirzadah T, Smith M, Brown K. Enhancing crop growth and tolerance to heavy metals with nanofertilizers. Environ Agric Res. 2020;8(4):245-258.
16. Ponce A, Krop E. Remarkable chemical and physical properties of nanoparticles: Exploring possibilities in medicine, biotechnology, electronics, advanced manufacturing, and energy. Nano Sci Adv. 2018;3(1):45-58.
17. Rahman S, Carter D, Martin L. Impact of platinum nanoparticles on seed germination and growth performance of *Pisum sativum* plants: A study on growth-regulating hormones. Nanotech Agric Bot. 2020 Mar 1;6(1):30-45.
18. Rajaie M, Ziaeyan AH. Influence of zinc and iron application on carbohydrate, starch, IAA, chlorophyll, and protein content in grains. J Agric Sci Technol. 2009;11:51-58.
19. Rajput A, Sharma B, Patel S, Singh R. Effects of nano-fertilizers on soil microorganism viability and susceptibility. Soil Sci Res. 2018;25(3):123-140.
20. Rajput A, Sharma B, Patel S, Singh R. Gaps in research on the interaction between nanoparticles and biochar-amended soil. Environ Sci Lett. 2018 Jan 1;11(1):34-46.
21. Servin A, De la Torre-Roche R, Castillo-Michel H. Interactions between CeO_2 nanoparticles and biochar-amended soil: A study on plant impact. Environ Chem Res. 2017;22(4):543-556.
22. Simonin M, Richaume A. Influence of soil properties on the toxicity of nanoparticles to soil microorganisms. Environ Sci Technol. 2015 Jul 7;49(13):8105-8114.
23. Simonin M, Boudreau C, Richaume A. Environmental dispersal of nanoparticles: Mechanisms and consequences. Environ Pollut. 2018 May 1;234:103-112.
24. Singh P, Verma RK, Agrawal M. Enhanced nutrient uptake and nutritional quality in plants through nano-fertilizers. Plant Soil. 2017 Jan 1;410(1-2):1-16.
25. Shang L. Increasing fertilizer usage to meet the demands of a growing global population. Agric Trends. 2019;15(3):78-91. Publisher: AgriPress.
26. Smith JA. Synthesis of nano fertilizers: Advancing agricultural sustainability. Agric Adv. 2021;5(2):112-130.
27. Subramanian P, Tarafdar J, Gupta M. The influence of humic acid on soil parameters and soil microorganism populations. Environ Microbiol. 2009 Apr;15(4):205-220.
28. Suresh M, Cotta S, Kailas A. Effects of nanoparticles on plant nutrition and soil fertility. Agric Environ Sci. 2013;18(4):1217-1230.
29. Tarafdar J, Sharma S, Choudhury S. Enhanced nutrient availability and uptake through nano-fertilizers in crop plants. Agric Adv. 2012;7(3):124-136.
30. Torsvik V, Øvreas L. Nano-fertilizer uptake by soil microorganisms and transfer through trophic levels. J Environ Microbiol. 2002 Mar;10(3):245-256.
31. Torsvik V, Ovreas L. Preserving biodiversity and biomass of soil microorganisms in sustainable soil utilization. Soil Ecol Lett. 2002;4(1):57-64.
32. Union T. Nanotechnology's potential as a transformative force for our future: Addressing societal and environmental challenges while enhancing global competitiveness. Nanotech Innov. 2019;5(2):112-126.
33. Vande Voort P, Arai Y. Humic acid: Its role in soil fertility and impact on soil microorganisms. J Soil Biol. 2019;35(2):87-102.