The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 20(1): 93-101, 2025 www.thebioscan.com

A COMPREHENSIVE REVIEW OF NANO-FERTILIZERS: THEIR ROLE IN ENHANCING AGRICULTURAL PRODUCTIVITY AND IMPACTS ON ANIMALS AND SOIL MICROBIOTA.

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DOI: https://doi.org/10.63001/tbs.2025.v20.i01.pp93-101

KEYWORDS

Nano-fertilizers, agricultural sustainability, microorganisms, nutrient delivery, crop productivity

Received on: 12-11-2024

Accepted on: 10-12-2024

Published on: 04-01-2025

ABSTRACT

Nano-fertilizers have the potential to meet plant nutrition needs, increase farmer profitability, and promote sustainable crop production without sacrificing yields. Nano-fertilizers effectively regulate nutrients in precision agriculture by matching crop growth stages and providing nutrients throughout the growth period. Nano-fertilizers improve the surface area available to various metabolic processes in the plant, accelerating photosynthesis and increasing crop yield and dry matter production. Nano-fertilizers effectively regulate nutrients in precision agriculture by matching crop growth stages and providing nutrients throughout the growth period. Nano-fertilizers boost crop growth up to the optimal concentrations. Increased fertilizer concentrations can harm crop growth due to toxicity.

By using techniques like targeted delivery, slow/controlled release, and conditional release, nanostructured formulations could more precisely release their active ingredients in response to biological demands and environmental cues. Research indicates that the utilization of nano-fertilizers improves the efficiency of nutrient utilization, lowers soil toxicity, limits the possible adverse effects of excessive dose, and decreases the frequency of application. Along with providing valuable information about the introduction of various nanoparticle forms in the agricultural industry, the research would help pave the way for a new path toward the nano-revolution.

This review highlights the challenges of current agricultural practices, the properties and applications of nano-fertilizers, and their contribution to the development of sustainable agricultural methods, synthesis of nanoparticles, effect of nano-fertilizers on seed germination, animals, soil microorganisms, etc., and toxicology followed by crop plants morph-physiological alternation after exposure to nano- fertilizers. It provides a foundation for future research into their effective and responsible use in agriculture.

INTRODUCTION

Agriculture in the modern world is dealing with a number of issues. On the one hand, the growing population is driving up demand for a vast number of foods; however the efficiency of input usage is declining, and the quality of the food and land is declining, which leading to an imbalance in the environment. Using more efficient Nanotechnology is the study of science, engineering, and technology at the nanoscale. It has the potential to reduce adverse impacts and direct agriculture in a sustainable

way. Nanometres are used to quantify it (Wheeler, 2005).
To increase soil fertility, agricultural produce productivity, and quality, nanotechnology is used to create or modify conventional fertilizers which is also known as nano-fertilizer, these fertilizers are produced by using extract from different plant reproductive or vegetative sections via a variety of chemical, mechanical, physical, or biological methods (Brunner et al., 2006). The two primary techniques for creating nanoparticles: (i) top-down and (ii) bottom-up methods. When top-to- bottom method is used, a material in large quantities is converted to nanoparticles. The bottom to up method uses atoms, molecules, and smaller monomers to create nanoparticles (Lee et al., 2020). Nanomaterials can help in nutrition regulation because of its increased penetration capacity. Crops can receive the right amount of nutrients via nano- fertilizers, which can regulate nutrient delivery in proper ratios, increasing productivity and maintaining sustainability. Nano-fertilizers' larger surface area, which comes from their smaller particle size helps in various metabolic processes. The nano-fertilizer's reactivity is excessively high because of their tiny size and large surface area, which also allow it to enter the plant system with ease and start working right away. The nanoparticles' diameters are less than those of plant roots and pores. As a result, it can readily penetrate plant systems (Tarafdar et al., 2012). Fertilizer with micro sizes smaller than 100 nm can be utilized for effective and environmentally responsible nutrient control lower pollution levels in the environment (Sultan et al.,2009). There are a very few literatures on nano-fertilizer role in sustainable agriculture. In this article we review challenges of present agricultural activity, types, properties of nano-fertilizer, their contribution to the development of sustainable agricultural methods, synthesis of nano particles, various effect of nano-fertilizers, and toxicology followed by crop plants morph-physiological alternation after exposure to nano-fertilizers. This comprehensive review helps in future research related to utilization of nano-fertilizers in system of agricultural sustainability.

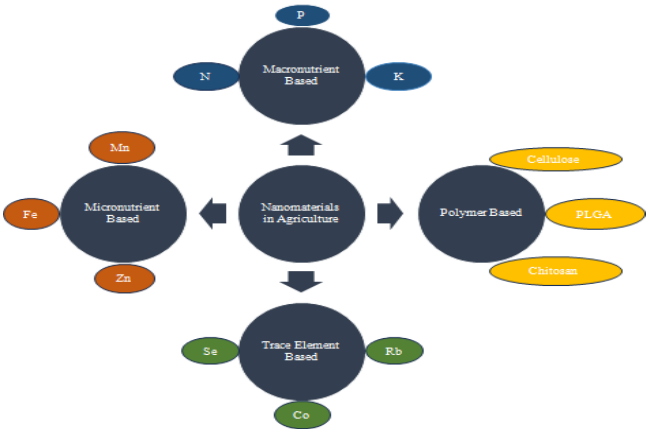

Fig 1: Types of Nano Fertilizer (Faizan et al., 2024; Gade, 2023)

3. Synthesis of Nanoparticles:

The three most popular approaches are chemical, biological, and physical. The techniques entail creating discrete phases based on the target nanostructured particles and bulk materials. The physical method uses a variety of processes, including evaporation, condensation, laser ablation, ball milling, melt mixing, and other biological approaches like bacteria, fungi, plant extracts, and enzymes, while the chemical procedures use sol gel, hydrothermal, polyol, and chemical vapour synthesis. Nanoparticles can be made in two ways: "bottom-up" and "top-down." Using a "bottom-up technique," smaller molecules are initially evaporated and their condensation is then regulated, allowing them to expand into larger particles. Using attrition and milling operations, a top-down approach reduces bulk materials into smaller, more desired nanoscale materials. Bottom-up nanofabrication often involves solid materials that are mechanically or lithographically processed using electron beams and photolithography (Rehmanullah et al., 2020) (Fig 2).

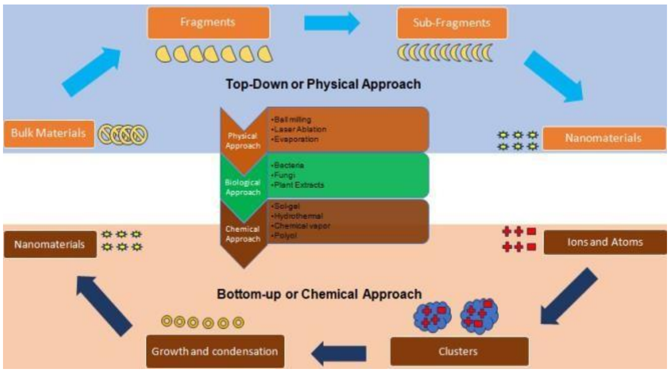

Fig 2: Various methods utilized for nanoparticles synthesis

4. Challenges of present-day Agricultural Practices

With an estimated 9.7 billion people on the planet by 2050, the demand for food is expected to increase by 70% (Cole et al., 2018). Meeting this demand presents a major challenge for agriculture, as it necessitates higher crop production levels. To achieve this, more fertile land must be brought under cultivation. However, this is increasingly difficult, as many agricultural lands are losing their fertility due to intensive and often unsustainable farming practices. Practices such as monocropping, overuse of irrigation, and improper soil management have degraded soil quality, reducing its ability to support healthy crops. This soil depletion is a significant obstacle to increasing food production and maintaining crop yields (Scarratt et al.,2021).
Along with soil degradation, agricultural productivity is also significantly hindered by the rising threat of plant diseases and pests. These pathogens not only limit the growth of crops but also affect their quality, leading to economic losses for farmers and food shortages. The impact of these biotic factors is further compounded by environmental factors such as changing climate conditions, which create a more favourable environment for the proliferation of these diseases and pests (Majeed et al., 2018). This creates a vicious cycle where the combination of soil degradation and increased pest pressures reduces the overall efficiency of agricultural systems.
To address soil fertility issues, there has been a heavy reliance on chemical fertilizers. While these fertilizers can temporarily boost crop yields by replenishing essential nutrients, their widespread use brings significant environmental consequences. Overuse of fertilizers pollutes water and damages aquatic ecosystems by producing nutrient runoff into bodies of water. This nutrient imbalance in water systems can lead to algal blooms, fish kills, and the destruction of biodiversity. Furthermore, excessive fertilizer use can cause soil acidification, which over time worsens soil health and makes it more difficult to maintain sustainable farming methods.
The cost of fertiliser purchases presents a major obstacle for small-scale farmers in many developing nations. These costs can be prohibitive, especially in places with little financial resources or low agricultural yield. Food security and agricultural sustainability are thus restricted since farmers in these areas frequently lack the funds to purchase the inputs required to sustain or boost output (Shuqin and Fang 2018).
Challenges in existing agricultural techniques, such as falling soil fertility, rising fertiliser costs, environmental repercussions, and farmers' financial troubles, pose a threat to the future of food supply. Innovative approaches that strike a balance between productivity and environmental and economic sustainability are necessary to achieve sustainable agricultural expansion.

5. Nanoparticles Properties:

5.1. The Particle Size of Nanoparticles

A crucial physical characteristic of nanoparticles that has a big influence on crop performance and nutrient utilisation efficiency is their size (Singh et al., 2024). Because it makes them available for the plants' metabolic activities, it is essential to guarantee that nanoparticles enter plant tissues (Sembada et al., 2024). The entry points of nanoparticles into plant systems, which dictate the particles' size, can be influenced via a number of pathways and methods (Khan et al., 2022). Through their roots, plants can absorb nanoparticles, which subsequently pass through the epidermal layers and enter the xylem to be transported to the plant's aerial portions. Foliar entrance is another popular pathway, where nanoparticles can enter through cuticular holes or stomata (Azim et al., 2023; Avellan et al., 2021). A nanoparticle's size affects its cellular entrance by influencing its translocation pathways, including inner attract, free translocation, outer wrapping, and embedment (Lin et al., 2022). It has been noted that smaller nanoparticles can effectively infiltrate the cell membrane and pass through the holes in the cell wall (Abbas et al., 2019; Rani et al., 2023).

5.2. The Surface Area-to-Volume Ratio of a Nanoparticle

Because of their small size, nanoparticles have an amazing property called a high surface area-to-volume ratio (Khan et al., 2019, Sohrabi et al., 2022). A material's volume indicates how much space it takes up, whereas its surface area is its entire outside covering (Greco et al., 2016). The surface area increases as the particle size decreases. Conversely, the surface area-to-volume ratio falls as the particle size rises (Andrievski, 2014). Because of this characteristic, nanoparticles are very successful as nano-fertilizers because they increase the surface area accessible for photosynthesis, which improves crop yields and sunlight absorption.

5.3. Shape of Nano-particle

The exterior form, outline, or contours of a substance, independent of its actual size, are referred to as its shape. But it's difficult to tell the difference between size and shape. Additionally, the shape changes as the particle sizes get smaller. Crushing and milling are the main processes that cause this change (Baig et al., 2021). The shape of nanoparticles is also influenced by synthesis-related variables including pH, reaction time, and temperature, which in turn impacts how well they work in agricultural applications (Rai et al. 2011, Sajanlal et al., 2011). The use of spherical silver nanoparticles (AgNPs) at a low concentration of 60 mg L^{-1} has been shown to successfully enhance a number of plant growth metrics in *Phaseolus vulgaris* (Verma et al., 2020). Higher concentrations of AgNPs were applied (Abd El-Aziz et al.,2019) and it was found that the number of leaves, plant height, and root length decreased. Lower quantities of silver nanoparticles may therefore improve germination and other aspects of plant growth.

5.4. Agglomeration

The physical characteristics and effectiveness of nanoparticles as nano-fertilizers are greatly impacted by agglomeration, which is the grouping of nanoparticles into bigger aggregates. It reduces their surface area, reactivity, and nutrient delivery capability by limiting movement through barriers like roots and causing uneven distribution within plant cells (Zare, 2016; Sharma et al., 2023). For instance, agglomerated TiO_2 nanoparticles were found to adhere to wheat cell walls, preventing root penetration, whereas well-dispersed ZnO nanoparticles were efficiently absorbed (Du et al., 2011). Modifying surface characteristics for improved dispersion, boosting zeta potential to improve electrostatic repulsion, and maximising pH and ionic strength to support stability are some ways to reduce agglomeration (Bini et al., 2022).

5.5. Crystalline Structure

The crystalline structure of nano-fertilizers influences nutrient release and plant uptake. Crystalline forms enable gradual nutrient release, improving efficiency, while amorphous forms offer rapid release but risk environmental impact. High surface reactivity in amorphous structures allows greater nutrient loading, enhancing soil properties and crop growth (Lestari, 2020; Carmona et al., 2022).

5.6. Charge Properties

The surface charge of nano-fertilizers is often either positive, negative, or neutral (Baddar, 2019). These nanoparticles' charge is influenced by the chemical makeup and functional groups that are present on their surface (Zhang et al., 2020). The mobility of nano-fertilizers, their interactions with soil particles, and their overall capacity to supply plants with nutrients are all significantly influenced by their surface charge. To maximise the usage of nano-fertilizers in agricultural applications, it is critical to comprehend and efficiently regulate this feature (Mirbakhsh, 2023). Aggregation is either encouraged or inhibited by surface charge characteristics. Depending on the kind and strength of the charges they display, charged nanoparticles can either attract or repel one another (Rodriguez-Loya et al., 2023). Electrostatic forces cause oppositely charged nanoparticles to be drawn to one another. Aggregates may form as a result of this event (Itatani et al., 2023, Dos Santos et al., 2019). On the other hand, similar-charged nanoparticles repel one another. Their dispersion in a solution is improved by this repulsion (Scarratt et al., 2021). The capacity of dispersed nanoparticles to be absorbed by plants and dispersed evenly within them makes them desirable.

6. Need for Nano-Fertilizers

Nanotechnology is revolutionizing agriculture with the development of nano-fertilizers which have unique properties such as high surface area, size of the particle should be less than 100 nm and improved reactivity. Compared to traditional fertilizers these fertilizers provide a number of significant advantages (Singh, 2017).

Crop production is increasingly reliant on nano-fertilizers. They improve the crop's development, quality and yield, which leads to higher yields and better food items suitable for human and animal use, as several studies have shown. Crop production is greatly increased by follicular application of nano-fertilizer (Tarafdar et al., 2012). By accelerating the reaction or synthesis process inside the plant system, nano-fertilizers provide the agricultural plant additional surface area and increased nutrient availability. Protein, sugar and oil content are among the plant quality metrics that are improved by this. The total quantity of protein, starch, chlorophyll, carbohydrates and IAA in the grain is increased when zinc and iron are applied to the plant (Ziaeyan and Rajaei, 2009). Specific nutrients also influence a plant's ability to withstand disease; due to their increased availability, The plant is shielded by these nutrients from biotic and abiotic stressors including illness and nutritional deficiencies. This suggests that nano-fertilizers improve the general health of the plant. ZnO nanoparticles also benefit stressed plants (Singh, 2017).

Compared to conventional fertilizers, nano-fertilizers are more ecological friendly due to their high efficiency and controlled nutrient delivery, which reduces pollution and nutrient losses.

7. Effect of Nano-Fertilizers on Seed Germination and Growth Metrics of plants

Nanotechnology represents burgeoning area of scientific inquiry with diverse applications across multiple fields, including agriculture. Recently several nano-fertilizers have entered the market, demonstrating potential for significantly enhancing crop productivity in a more cost-effective manner compared to traditional fertilizers (Sahoo et al., 2022).

Some findings have indicated that the application of Nano-urea (100%) in conjunction with NPK reduced the time required for 50% germination (Sahoo et al., 2022). Additionally, it was noted that nano-urea (100%) combined with NPK enhanced the dimensions of the leaf and the surface area of the leaf (Sahoo et al., 2022). Again, study conducted on the impact of nanoparticle-based fertilizers on the germination of seeds and initial growth phases of bitter almond seedlings, particularly in relation to traditional chemical fertilizers when subjected to saline environments. Findings indicated that pre-treating the rootstock of bitter almond seeds utilizing 50% nano-fertilizers in saline environment significantly improved germination rates, as well as increased stem length and diameter compared to urea, ammonium sulfate fertilizers (Badran and Savin, 2018). Application of TiO_2

NPs and Humic acid positively influenced the physiological aspects of lettuce plants by boosting biomass and enhancing biochemical pathways that elevate the levels of bioactive compounds (Ahmed et al., 2024). Application of nanoparticles at 200 ppm resulted in increases in yield of soybean seeds 32.60%-40.12% under arid and irrigated condition in contrast to plants that have not received treatment (Dola et al., 2022). Nano-iron treatment elevated the oil content of soybean seeds was measured at 10.14% under drought conditions and 7.87% under well-watered conditions (Dola et al., 2022).

8. Nutritional value of Nano-Fertilizers

Nano-fertilizers represents an innovative strategy for nutrient conservation, particularly for nitrogen, while also contributing to environmental conservation. The use of nano-fertilizers can substantially improve nutrient use efficiency, as evidenced by the 50% reduction in urea through the application of two sprays of Nano Nitrogen (Kumar et al., 2020). The broadcast application of POCF (polyolefin-coated fertilizers) on green pepper (*Capsicum annuum* L.) yielded the highest results, while the band application of POCF and the RAF (rapidly available fertilizers) produced comparable outcomes (Ombodi and Saigusa, 2000). Mesoporous Silica nanoparticles system featuring 3nm pores can effectively deliver DNA and various chemicals into isolated plant cells as well as intact leaves (Torney et al., 2007). Biosensor utilizing nanomaterials offer a promising solution for rapid, sensitive, efficient and portable detection, effectively addressing the limitations of conventional methods for detecting food contaminants (Lv et al., 2018).

9. Nano-Fertilizers Effect on Animals

The potential hazards of nanoparticles to animals were investigated through studies on mice. Liu et al., (2010) stated that the poisonousness of silver (Ag), zinc oxide (ZnO), and titanium oxide Nanoparticles vary in size and form, chemical composition, and dose, with potential to inflict oxidative damage to the spleen's immune system. Brohi et al., (2017) and Liu et al., (2010) further indicated that a dose of 200 mg/kg of nano of nano-ZnO had mild effects on liver, kidney, heart function, and sperm vitality, whereas higher doses significantly impaired these functions, causing kidney and liver damage, cardiac dysfunction, and sperm abnormalities.

According to findings from studies on animal development and reproduction, females are especially vulnerable to nanoparticle toxicity, which can harm foetal development. In a research on pregnant mice, administering 100 micrograms of titanium dioxide (TiO_2) nanoparticles (<300 nm) on gestational days 3, 7, 10, and 14 permitted the nanoparticles to cross the placenta and reach the foetus. This included the transmission of gold (Au), TiO_2, and silicon (Si) molecules to fatal testes, sertoli cells, and sperm, causing fatal weakening. Similarly, inhalation of nanoscale cadmium by pregnant animals negatively impacted their offspring (Brohi et al., 2017).

The hazardous properties of nanoparticles is closely associated with the generation of reactive oxygen species (ROS), which can damage animal organs by inducing oxidative stress. This stress causes severe tissue damage and programmed cell death (apoptosis) (Khanna et al., 2015; Manke et al., 2013; McShan et al., 2014).

According to research, nanoparticles' detrimental impacts are mostly caused by excessive levels of reactive oxygen species (ROS). These ROS molecules act like tiny attackers, targeting animal organs and creating oxidative stress—a state where the body's defences are overwhelmed. This stress can lead to severe tissue damage and even induce cell death. (Khanna et al., 2015; Manke et al., 2013; McShan et al., 2014).

Nanoparticles can damage blood cells, the liver, the lungs, the eyes, the skin, and the reproductive system. Their capacity to accumulate in non-target tissues makes them more harmful, since they frequently cause oxidative stress, DNA damage, or toxic effects on the blood (Elalfy et al., 2018). Recent research has also revealed possible dangers in agriculture, such as weight loss in cattle fed selenium nanoparticles (SeNPs). Chemical alterations in selenium or its incorporation into selenoproteins may raise the risk of death (Bano et al., 2022).

10. Nano-Fertilizers Effect on Soil Microorganisms

Knowledge regarding how nano-fertilizers affect the soil microbiome is currently scarce despite the fact that microorganisms are highly sensitive and significant objectives for assessing the detrimental effects of nanomaterials (Gupta et al., 2020). In addition to promoting the development of plants, the gradual and steady discharge of micronutrients made possible by nano-fertilizers preserves the variety of the advantageous microbiota (Ameen et al., 2021).

The composition and activity of the microbial communities that live in soils and the phyllosphere are influenced by nano-fertilizers. Since soil, roots, and leaves are the primary habitats for the application of nano-fertilizers, knowledge of how these substances affect these populations of microbes is essential. The long-range effects on the plant-associated microorganisms will be primarily determined by how nano-fertilizers affect the bacteria that occupy such environmental niches (Kalwani et al., 2021).

11. Nano Toxicology

There are certain toxicity-related dangers, nanoparticle possess even though Nano particles' application as fertilizers to boost agricultural output and increasing the availability of plant nutrients is growing in popularity (Nongbet et al., 2022). Although nanotechnology has several advantages that merit investigation in order to address some challenges, we must be mindful that its careless application may result in a number of problems for plants, animals, and ultimately humans (Mishra et al., 2019). Because these tiny particles have the capacity to enter biological systems more deeply and provide significant risks, nano particles' toxicity, safety, and environmental impacts (Kumar et al.,2022).

Despite being used to supply plants with nutrients, nano particles' nanotoxicity continues to be a worry for both the environment and people (Khan et al., 2021). When compared to biological methods, physical and chemical processes produce more hazardous nanoparticles. Additionally, compared to metal and metal oxides, nano particles, organic nano particles are less detrimental to soil microorganisms (Jaskulski et al., 2022).

Numerous metal oxide compounds, including titanium dioxide, zinc oxide, silver oxide, $Fe2O_3$, copper oxide, ZrO_2, and MoO_3, possess photocatalytic properties (Sharma et al., 2018) to increase reactive oxygen species production and photocatalytic activity (Bishoge et al., 2018). However, the aforementioned catalysts' degradation processes are mostly used in wastewater treatment to get rid of stubborn and persistent contaminants like colours and pharmaceuticals (De Santiago Colín et al., 2018), (Hernández et al., 2020). There are currently no well-substantiated toxicological investigations since at low quantities, the residual nano particles in the effluents are believed to be innocuous, but can be harmful to humans and animals at high quantities (Garcia-Mier et al., 2019).

Among the factors that correlate with the toxic level of nano particles are surface activity, alteration, aggregation, size, and number; The concentration of nano particles does not determine its lethal level, nor does its toxicity correlate with the dose in relation to mass (Paramo et al., 2020). Knowing the impact that specific nano particles may have when interacting with a live system is challenging. First, the created effects are mostly caused by the nano particle's physicochemical properties. In addition to their physicochemical characteristics, the experimental design, synthesizing, exposure time over the plant, developmental stage at which the nano particle gets into contact with the plant, and the approach of introduction and interaction of the nano particles affect the nano particles' toxicological consequences (Corredor et al., 2009).

12. Limitations and Complications with Nano- Fertilizers

Significant barriers to the widespread use of nano-fertilizers under diverse pedoclimatic circumstances over the entire world are their increased price when compared to traditional fertilizing techniques and the fact that their formulation is not standardized, which affects the same plants differently depending on the location (Zulfiqar et al., 2019).

There is currently a lot of "micron"-sized products on the market that are not truly "nano" fertilizers, which further implies that nano-fertilizers are not being closely monitored. Long- term persistence in plant systems is severely harmed by these particles (Al-Juthery et al., 2021). The relationship between nanomaterials and other pollutants, such heavy metals, is one crucial factor to take into account. While certain nano particles may enhance the toxic effect of specific substances, Heavy metals could be absorbed by others to protect plants and restore soil (Hu et al., 2014).

Delivering essential micronutrients to crops with delivery systems based on nanotechnology using nanoparticles is still relatively new and needs more study (Lang et al., 2021). Due to their lack of understanding, fear of the high cost, and doubts about their efficacy in comparison to conventional fertilizers, farmers and other agricultural stakeholders may be reluctant to embrace innovative technologies like nano-fertilizers (Chahande and Sharma, 2023).

Nano-fertilizer manufacturing on a lab scale has demonstrated potential, but scaling it for commercial agricultural use poses challenges, especially in terms of ensuring consistency and uniformity in output (Bhardwaj et al., 2022). Nanomaterials' potential impacts on biodiversity, the ecosystem, and human health continue to raise questions regarding their use. Since regulatory systems for nano-fertilizers are still developing, this uncertainty may prevent them from being widely adopted (Rajput et al., 2021).

13. Crop Plant Morpho-Physiological Alterations Following Nano-Fertilizers Exposure

Table 1: Crop Plant Morpho-Physiological Alterations Following Nano-Fertilizer Exposure

SL No	Crop Plant	Nanofer -tilizer	Morpho-physiological Changes	References
1	*Triticum aestivum* L.(Wheat)	ZnO NPs	Both the plant's height and leaf count rise.	Nazir et al., 2024
2	*Cicer arietinum L.* (Chickpea)	Fe, Zn and NPK	Height of the plant and weight of the seed increases.	Drostkar et al., 2016
3	*Cucumis sativus L.* (Cucumber)	Liquid nano NPK	Improvement in height, leaf count and fruit quality.	Merghany et al., 2019
4	*Caesalpinia bonducella* (L.)	ZnO and MgO	Increases in height	Khalid et al., 2022
5	*Triticum aestivum* L. (Wheat)	Fe NPs	Enhanced plant growth, spike length, numbers	Hanon Mohsen et al., 2022
6	*Coffea arabica L.* (Coffee)	ZnO NPs	Accelerated root and leaf growth.	Rossi et al., 2019
7	*Abelmoschus esculentus* (L.) Moench (Okra)	Se NP	Improvement in fruit production, length of the shoots and roots.	Sonali et al., 2024
8	*Eleusine coracana* (L.) Gaertn. (Finger millet)	CaP-U NPs	Increase in growth characteristics such as shoot length, root size, and leaf area.	Mishra et al., 2023
9	*Coriandrum sativum* (Coriander)	CuNPs	Decrease in length of root, biomass and chlorophyll content.	AlQuraidi et al., 2019
10	*Capsicum annuum* L (Sweet pepper)	Fe and Zn NPs	Positive increase in height of plant, leaf area and fruit	Assi et al., 2020

14. Applications

Nano-fertilizers have a bigger surface area because of their incredibly small particle size allowing them to support plant metabolic processes on a greater number of locations. By boosting photosynthetic activity, this enhances plant growth and nutrient use efficiency. The tiny particle size of nano-fertilizers facilitates their entry into plant tissues through the roots or leaves, increasing nutrient absorption and decreasing losses due to leaching, volatilization, and fixation, especially for nutrients like NH_4-N and NO_3-N (Liscano et al., 2000). Fertilizers in nanoparticle form will improve agricultural plants' access to and absorption of nutrients. For instance, zeolite-based nano-fertilizers provide nutrient availability throughout the plant's development period by releasing nutrients gradually (Joseph and Morrison, 2006).

It has been demonstrated that nano-fertilizers significantly improve seed germination, seedling health, and overall plant development. Nano-fertilizers increase the availability of nutrients for developing seedlings, leading to longer roots and shoots, because they are readily absorbed by seeds. For example, nano-ZnO has demonstrated superior germination and root development in peanuts when compared to bulk zinc sulfate (Prasad et al., 2012). Positive effects on soybean germination, dry matter yield and chlorophyll synthesis have been demonstrated by both nano-SiO_2 and nano-TiO_2 (LIU et al., 2005). However, excessive usage of nano-fertilizers may have negative consequences; for instance, it has been shown that ZnO nanoparticles prevent Allium sativum roots from growing (Shaymurat et al., 2012).

Important growth indicators including plant height, dry matter production, leaf area, and photosynthesis rates are all improved by nano-fertilizers. Higher yields and improved quality result from their efficient transfer of photosynthates from leaves (source) to economically valuable plant parts including grains, tubers, and fibers (sink) (Braun and Roy, 1983). For instance, nano-K fertilizers have been linked to more seeds per panicle (Tabrizi et al., 2009), while nano-iron treatments have raised the quantity of iron in plants (Nadi et al., 2013).

15. Conclusion

Even if some nanoparticles have been shown to be dangerous, nanotechnology is still the best option for improving the agriculture industry.

Increased crop yield through the use of various nano-fertilizers will lower agricultural product ion fertilizer costs and reduce pollution risks. The benefits of this innovative technology for agriculture include the recovery of depleted soil nutrients, the use of green nano-chemicals to control pests and herbs, the provision of macro and micronutrients for healthy plant growth, nutrient absorption, food crop security, nanofood and nutrient delivery, food packaging, etc. Applications of nanotechnology in agriculture show enormous promise for enhancing the environment and raising crop plant yield and quality. At ideal doses and concentrations, nano-fertilizers improve crop growth and yield. However, greater concentrations may impede plant development and productivity. This phenomenon raises awareness of innovative nanomaterial- based technologies for soil enhancement and agricultural production. The usage of nano-fertilizers in agriculture is something that society ought to be more concerned about. The efficient application of nano-fertilizers can improve crop production's fertilizer nutrient use efficiency. Nano chemicals offer superior characteristics and novel applications due to their quantum sizes and surface area. However, they may have certain hazardous impacts on the environment when applied as fertilizers, insecticides, nano delivery instruments, food packaging and so on.

Although it is unknown exactly how nanomaterials (NMs) interact with plants, such research could be useful in the future. The expansion of the application of NMs in agriculture and, more importantly, in plant science research is anticipated to depend on the effectiveness of interdisciplinary collaborative approaches to close the knowledge gap regarding the relationship between nanotechnology and plants.

Acknowledgement

The authors sincerely express heartfelt gratitude to the Department of Botany, Basugaon college for their utmost support and guidance.

Competing Interest

Authors have declared that no competing interests exist.

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