Deep Science Publishing
https://doi.org/10.70593/978-93-49307-12-4_3

Chapter 3

Nano-Engineered Fertilizers: Enhancing Plant Nutritional Dynamics through Precision Delivery

Nirmal Kumar Kumawat*, K. N. Shah, V. Singh and D. K. Rana

Department of Horticulture, School of Agriculture and Allied Science, H.N.B. Garhwal University, Srinagar Garhwal, Uttarakhand
**Email:* kumarkumawatnirmal@gmail.com

Abstract: Nano-fertilizers enhance crop growth, yield, and nutrient use efficiency while reducing fertilizer wastage and cultivation costs. They enable precise nutrient management in precision agriculture, ensuring sustained nutrient availability throughout crop growth. At optimal levels, they boost photosynthesis and dry matter accumulation, but excessive concentrations may cause nutrient toxicity. Nano-fertilizers also improve plant resilience to biotic and abiotic stresses. With limited arable land and water resources, improving resource efficiency is crucial for sustainable agriculture. Nanotechnology offers targeted delivery, controlled release, and minimized soil toxicity, reducing application frequency and environmental impact. Its potential extends to biomedicine, environmental engineering, and water management, making it a transformative tool for global sustainability.

Keywords: Agriculture crop, Nanofertilizers, Plant nutrition, Nanoparticle, Sustainable development

Citation: Kumawat, N. K., Shah, K. N., Singh V. & Rana D. K. (2025). Nano-Engineered Fertilizers: Enhancing Plant Nutritional Dynamics through Precision Delivery. In *Eco-Friendly Nanotechnology: Harnessing Small-Scale Technologies for a Cleaner and Healthier Planet* (pp. 29-44). Deep Science Publishing. https://doi.org/10.70593/978-93-49307-12-4_3

1 Introduction

A Second Green Revolution is becoming more and more necessary as a result of the First Green Revolution in the 1970s, which concentrated on four important aspects of the production system: semi-dwarf high-yielding rice and wheat varieties, extensive use of irrigation, fertilizers, and agrochemicals. However, agricultural productivity has now plateaued, which has had a detrimental effect on the livelihoods of the farming community. Nanoscale science and nanotechnology are anticipated to have the potential to revolutionize agriculture and food systemsBoopati and Chinnamuthu (2009). Tokyo Science University professor Norio Taniguchi coined the term "nanotechnology" in 1974. The term "Nanotechnology," or "Nanotech," describes the study of atomic and molecular-scale matter manipulation. It covers the creation of materials or devices within the size range of 1 to 100 nm, with a primary concentration on structures in this range.

At the nanoscale, matter displays properties that differ significantly from those at the macroscopic level. The modifications in characteristics arise from the diminished molecular size and the modified interactions among molecules. The characteristics and prospective uses of nanotechnology, crucial for the agricultural revolution, encompass strong reactivity, improved bioavailability and bioactivity, as well as adhesion and surface impacts of nanoparticles (Gutierrez *et al.*, 2011). Customized items are composed of atoms, and their characteristics are determined by the configuration of these atoms.

In order to increase productivity per unit area, global agricultural cropping systems heavily rely on fertilizers, insecticides, and herbicides. However, using these chemicals and fertilizers in amounts higher than what is recommended causes a number of problems, including pollution of the environment (air, water, and soil), low input efficiency, poor food quality, the development of resistance in weeds, diseases, and insects, decreased production income, soil degradation, deficiencies in micronutrients in the soil, and toxicity to beneficial organisms above and below the soil surface. The need to feed the world's expanding population is growing in spite of these obstacles (Braun & Roy, 1983). Future initiatives must thus concentrate on creating wholesome agricultural products that are high in protein and other vital elements for consumption by humans and animals. This calls for a focus on producing food of superior quality that includes the necessary amounts of protein and nutrients. Nano-fertilizers, insecticides, and herbicides can be useful instruments for improved nutrient and pest control in order to solve these problems in crop production. Future initiatives must thus concentrate on creating wholesome agricultural products that are high in protein and other vital elements for consumption by humans and animals. This calls for a focus on producing food of superior quality that includes the necessary amounts of protein and nutrients. Nano-fertilizers, insecticides, and herbicides can be useful instruments for improved nutrient and pest control in order to solve these problems in crop production.

2 What are nanoparticles?

A particle is considered a nanoparticle if at least one of its dimensions is less than 100 nm. One billionth of a meter, or 1 nm, is equal to 10^{-9} meters. To put it in perspective, a virus is about 100 nanometres in size. In other words, "nano" is not always bad because humans have been exposed to nanoparticles for as long as there have been people. It can be challenging to understand the scope of nanotechnology (Zhang *et al.,* 2018). A nanometre is 10^{-9} of a meter, or one billionth of a meter. To put this in perspective: An inch is made up of 25,400,000 nanometres. The thickness of a newspaper sheet is roughly 100,000 nanometres. The Earth would then be one metre in size (Nair *et al.,* 2010).

Nanoparticles possess unique properties, including a high proportion of surface atoms, allowing them to penetrate plant and animal cell walls. This ability enables nanotechnologists to deliver substances at the cellular level, making the process more effective than conventional methods. Additionally, these particles exhibit high surface energy and experience spatial confinement, enhancing their functionality (Wang, Z. L., 2000).

3. Nano fertilizers

Using chemical, physical, mechanical, or biological processes with the aid of nanotechnology, nano-fertilizers are modified or synthesised versions of conventional fertilisers, bulk fertiliser ingredients, or extracts from different vegetative or reproductive portions of plants. The purpose of these fertilisers is to increase soil fertility, agricultural product quality, and productivity. Bulk materials can be converted into nanoparticles (Chhipa & Gupta, 2018). Nanoscale materials have different chemical and physical characteristics than bulk materials. Utilizing rock phosphate in its nanoform could make more phosphorus available to plants. Since there are no silicic acid, iron, or calcium ions to bind the phosphorus, phosphorus fixation in the soil can be avoided by directly applying nano-sized rock phosphate particles to crops. As a result, crop plants have greater access to phosphorus (Sahoo, U., *et al.*, 2017).

4 Need of nano fertilizers

The repercussions of Green Revolution weariness are being felt in Indian agriculture. From 0.5 million tonnes in the 1960s to 24 million tonnes in 2013, fertilizer usage has grown rapidly over the last 50 years. This growth coincides with a four-fold increase in food grain production, reaching 254 million tonnes (Raliya & Choudhury, 2017). Despite the success of grain production, it has been noted that a decrease in the amount of organic matter in soils and uneven fertilization have caused the yields of many crops to plateau. While the present ratio in India is 10:2.7:1, the ideal NPK (nitrogen, phosphorus, and potassium) fertilizer ratio for crop productivity is 4:2:1. Due to significant government subsidies, nitrogenous fertilizers especially urea are applied more frequently than other nutrients (Mukhopadhyay, 2014).

In places that receive irrigation, the fertilizer response ratio has drastically dropped from 13.4 kg of grain per kilogram of nutrient supplied in the 1970s to only 3.7 kg in 2005. This suggests that in order to produce the same amount of grain, more fertilizers are needed. For instance, in 1970, one tonne of grain required 27 kilogram of NPK per hectare, whereas in 2008, the same output required 109 kg of NPK per hectare (Tewatia, 2012). Compared to the current consumption level of 23 million tonnes, India will need 45 million tonnes of nutrients to reach the aim of 300 million tonnes of food grains and feed the expanding population of 1.4 billion by 2025. A startling rise in the severity of multinutrient deficiencies is causing crop losses of almost 25–30%. The following are India's rates of key nutrient deficiencies: Nitrogen is 89%, phosphorus is 80%, potassium is 50%, sulfur is 41%, zinc is 49%, and boron is 33%. (Moraru *et al.*, 2003; Chau *et al.*, 2007).

In light of these challenges, India needs a Second Green Revolution. Nano-fertilizers are expected to have the potential to revolutionize agriculture and address some of these pressing issues. Indian agriculture is experiencing the consequences of the fatigue of the Green Revolution. Over the past 50 years, fertilizer consumption has increased exponentially from 0.5 million tonnes in the 1960s to 24 million tonnes in 2013, resulting in a four-fold rise in food grain production, which reached 254 million tons. Even though grain growth has been overwhelmingly successful, it has been noted that many crop yields have started to plateau due to uneven fertilization and a decrease in soil organic matter. While the current ratio is maintained at 10:2.7:1 in India, the ideal NPK fertilizer ratio for crop productivity is 4:2:1. Due to significant government subsidies, nitrogenous fertilizers—particularly urea—are used more frequently than other nutrients. In the country's irrigated regions, the fertilizer response ratio dropped from 13.4 kg grain/kg nutrient applied in the 1970s to only 3.7 kg in 2005. (Roberts, T. L., 2008).

In other words, larger quantities of fertilizers are needed to produce the same amount of grain output. For example, in 1970, 27 kg of NPK per hectare was required to produce one tonne of grain, whereas in 2008, the same level of production could only be achieved with 109 kg of NPK per hectare. The nation will need 45 million tonnes of nutrients, compared to its current consumption level of 23 million tonnes, in order to meet the target of 300 million tonnes of food rains and feed the growing population of 1.4 billion by 2025 (Kuzma, 2007; Scott, 2007). A crop loss of roughly 25–30% is closely linked to the startlingly rising prevalence of multinutrient deficiencies each year. The extent of multi-nutrient deficiencies is alarmingly increasing each year, closely associated with crop losses of nearly 25–30%. Nutrient deficiencies in the country are observed as follows: 89% for N, 80% for P, 50% for K, 41% for S, 49% for Zn and 33% for B. in need of a Second Green Revolution. Nano fertilizers are considered to have the potential to transform agriculture (Tewatia, 2012; Patil, 2009).

5 Mode of nano fertilizers deliver nutrients

5.1 Applications of nanotechnology in agriculture

Nanotechnology is increasingly providing various nanodevices and materials that play a unique role in agriculture. For site-specific water and nutrient management, these include nano biosensors that can identify the soil's moisture content and nutrient status. While nano-herbicides provide targeted weed control in agricultural fields, nano-fertilizers facilitate effective nutrient management. Seed vigor can be increased by nanonutrient particles, and pest control can be improved by nanopesticides. Additionally, alginate and chitosan nanoparticles can be used as carrier materials for herbicides, such as paraquat (Ghaly, 2009). Nano-herbicides are particularly effective in weed management. Accordingly, nanotechnology contributes significantly to crop production by providing ecological sustainability, economic stability, and environmental safety (Gutierrez *et al.*, 2011). Nanotechnology-created nanoparticles can be incorporated into the entire agricultural production system's value chain. (Hamid, 2012).

5.2 Application of Nano fertilizer

Nanotechnology is used to create synthetic or modified forms of conventional fertilizers, bulk fertilizer materials, or extracts from different plant parts that are vegetative or reproductive. These products can be made chemically, physically, mechanically, or biologically. These fertilizers are used to increase agricultural product quality, productivity, and soil fertility. Bulk materials can be converted into nanoparticles. (Hediat & Salama, 2012). The physical and chemical properties at the nanoscale differ from those of bulk materials. For example, when rock phosphate is used in its nano form, it may increase the availability of phosphorus to plants (Joseph & Morrisson, 2006). Since there are no silicic acid, iron, or calcium ions to fix the phosphorus, applying nano-sized rock phosphate particles directly to crops can stop it from happening in the soil. This increases crop plants' access to phosphorus.

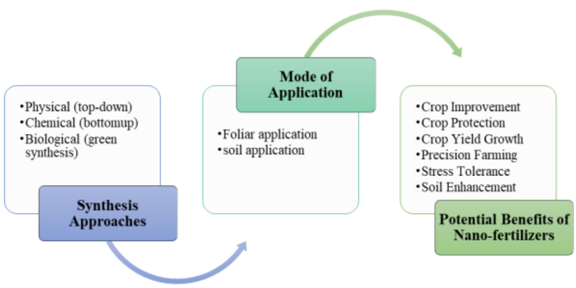

Fig. 1. Application and uses of Nano fertilizer

5.3 Impact of nano fertilizers on plant growth

Nanotechnology is becoming more and more important in crop production because of its enormous potential to improve fertilizers' current state in terms of sustainability, ecological safety, and economic stability. Because of its large surface area, enhanced catalytic surface, chemical reactivity, rapid dispersibility, and water-adsorption capabilities, nanotechnology has garnered special attention as a means of increasing crop productivity and resource efficiency. These unique properties of nanomaterials make Because of their special qualities, nanomaterials are a promising way to deliver nutrients to crop plants, outperforming a variety of conventional fertilizers (Naderi & Danesh-Shahraki, 2013).

Nano-fertilizers are thought to be a good way to boost crop yields because they slow down the release of nutrients, which lowers the frequency of fertilizer applications and greatly increases nitrogen use efficiency (NUE), a crucial indicator of crop yield (Kah *et al.*, 2019). (i) Plant nutrient uptake; (ii) Transport of nutrients to the above-ground parts of the plant; (iii) Utilization of nutrients and biomass growth; and (iv) Environmental factors form the basis of the concept of nitrogen use efficiency. (Renner *et al.,* 2020).

Nano-fertilizers, when applied to soil, first come into contact with plant roots, promoting growth by facilitating the uptake of essential nutrients necessary for protein synthesis. Additionally, as reported in wheat (Abdel-Aziz *et al.*, 2018), millet (Tarafdar *et al.,* 2014), and cotton (Rezaei & Abbasi, 2014) crops, nano-fertilizers contribute to the breakdown of carbohydrates, the release of hormones within plants, and the synthesis of various proteins and indole acetic acid (IAA). Nano-fertilizers have been shown to increase chlorophyll content, which improves the plant's capacity to absorb sunlight, pigmentation, Rubisco activity, CO_2 metabolism, and photosynthetic efficiency (Gao *et al.,* 2006; Yang *et al.,* 2006). Additionally, nanofertilizers improve the assimilation of nitrogen (N) and phosphorus (P), which stimulates photo-reduction activity for photosystem II and electron transport chains and greatly facilitates the detoxification of reactive oxygen species. (Janmohammadi *et al.,* 2016; Morteza *et al.,* 2013).

According to studies on Phaseolus vulgaris L. (El-Saadony & Desoky *et al.*, 2021) and cucumber plants (Siddiqui *et al.,* 2014), the use of nano-fertilizers not only enhances N and P uptake but also reduces a variety of abiotic stresses. At different phases of growth, plants encounter abiotic stressors and nutrient deficiencies that can cause oxidative stress, damage membranes, and impede root development. It is evident from the data presented in this chapter and from earlier research that nano-fertilizers provide an economical and environmentally beneficial method of promoting plant growth.

6 Distribution of nutrients in soil after application of nano fertilizer

Phosphorus and nitrogen are vital nutrients that plants need for food security and sustainable crop production. These nutrients are not available for plant uptake, though, due to their high rates of immobilization and leaching in soil. By employing nanotechnology to intercalate or trap nitrogen in a clay matrix, nitrogen utilization efficiency can be increased. Zeolites can be used in the creation of nano-fertilizers because of their special qualities, such as their large surface area. Similarly, potassium nitrate can be released gradually using nanomaterials made from carbon-based graphene oxide, which reduces leaching. (Shalaby *et al.*, 2016). According to studies, urea-treated zeolite improved maize's nitrogen uses efficiency (NUE) by 15% when compared to urea alone (Ahmed *et al.*, 2008). Modified zeolites containing NH_4NO_3 and KNO_3 released NH_4+ more slowly than traditional fertilizers, as Komarneni (2009) showed. The following factors contribute to the slow release of nitrogen (N) from nano-zeolite: (1) urea leaching from the plant root zone is prevented; (2) urea is converted slowly by soil enzymes, delaying the formation of NH_4+ ions; and (3) ammonium ions are adsorbed onto zeolite exchange sites, rendering them unavailable to nitrifying bacteria (Subramanian & Thirunavukkarasu, 2017). The literature claims that nano-zeolite can release nitrogen for 1176 hours, while conventional fertilizers can only do so for 200 hours (Subramanian & Rahale, 2012). Furthermore, N can be released by hydroxyapatite nanoparticles for longer than 60 days. (Kottegoda *et al.,* 2011).

Phosphorus (P), which is released by soil organic matter, is instantly bound to insoluble inorganic compounds, causing a P deficit and stunted plant growth. This implies that the use of modified zeolites or positively charged nanoparticles can increase the amount of phosphate present in the soil. Since hydroxyapatite nano fertilizers interact weakly with soil components in comparison to charged ions ($PO4^{3-}$, $HPO4^{2-}$, $H_2PO_4^-$, or Ca^{2+}), it has been reported that their synthesis can effectively control the release of P and increase crop yield with minimal risk of P loss (Liu & Lal, 2015). Compared to traditional P fertilizers, this maximizes the retention of hydroxyapatite nano fertilizers in the soil solution, increasing the effectiveness of P absorption by plant roots. Additionally, nano-zeolites can act as efficient phosphate sorbents, promoting the soil's gradual release of P. According to reports, ammonium-charged zeolites can improve the solubility of minerals, particularly phosphate, thereby raising the amount of phosphorus available in the soil. (Dwivedi *et al.,* 2016).

The cation exchange capacity (CEC) of the soil, which measures the soil's capacity to hold onto potassium and other crucial cations for crops, is the main factor influencing the availability of potassium, which is labile in soil. Clay minerals and soil organic matter are the two main elements of soil that support CEC. Plants can receive more potassium from the soil when the CEC capacity is higher. However, many soils lack enough clay minerals and organic matter as a result of intensive agriculture, which limits the number of potassium adsorptive sites. Because of their high ion exchange capacity, nano-fertilizers, especially those based on zeolites, can therefore increase potassium concentration by releasing potassium gradually. (Liu *et al.*, 2005; Zhou & Huang, 2007).

7 Effects of nano fertilizers on the bioavailability of heavy metals and vital nutrients

The adsorption of heavy metals and raising soil pH, nanoparticles reduce the bioavailability of heavy metals (Zhou *et al.*, 2021). Fe_3O_4- nanoparticles, for instance, decreased the soil's ability to move cadmium and other heavy metals (Sebastian *et al.*, 2019). A three-year-long study revealed that silicon nanoparticles changed Cd into a more stable component in the soil (Wang *et al.*, 2020). According to Cui et al. (2018), nano-hydroxyapatite improved the pH of the soil and decreased the amount of interchangeable acid and aluminum present. In a different study, applying 0.05%, 0.2%, and 0.4% nano-Fe3O4-modified biochar to brown rice resulted in a significant decrease in its Cd content of 48.9%, 35.6%, and 46.5%, respectively, while soil Cd bioavailability decreased by 6.81% to 25.0%. (Zhang *et al.*, 2020). According to Liu et al. (2015) and Liu & Lal (2015), silicon nanoparticles improve plant growth by increasing nutrient phytoavailability in plants. With values of 235.48 mg Cu kg^{-1} and 164.84 mg Ce kg^{-1}, respectively, Peng et al. (2020) found that the application of 500 mg kg^{-1} CuO-nanoparticles and CeO-nanoparticles promoted the aggregation of copper (Cu) and cerium (Ce) metals in the rice's subsurface sections. In contrast, after being treated with the highest ZnO-NPs, the amount of zinc (Zn) in the plant's aboveground sections was 313.18 mg kg^{-1}, with a translocation factor of 1.5. Additionally, the biggest decrease in metal aggregation in brown rice was achieved by foliar application of Si-NPs at a concentration of 20 mg L^{-1} (Hussain *et al.*, 2020). This application decreased metal accumulation while simultaneously increasing grain yield and quality. The application of selenium (Se) and Si-nanoparticles topically at a 20:10 mg L^{-1} ratio enhanced the bioavailability of Se in grains by 86%. (Hussain *et al.*, 2020).

According to a different study, foliar application of nano-Si dramatically decreased the translocation factor from the topmost nodes to the rachises, but it significantly increased the translocation factors of iron, magnesium, and potassium (K) from the uppermost nodes to the rachises. Furthermore, it was discovered that the reduction of the translocation factor of Cd from subterranean plant parts to the uppermost nodes and rachises was most significant at higher levels of nano-Si (25 mm) (Chen *et al.*, 2018). While lowering the translocation factor of heavy metals from belowground to aboveground parts and/or from shoots to grains, both organic and inorganic nano-Si decreased the content and bioconcentration factor of heavy metals in grains. The most notable effect was observed for Cd. With inorganic and organic nano-Si, the average grain Cd content dropped by 27.1% and 23.8%, respectively (Wang *et al.*, 2016). However, when compared to the control, the application of K-nano-chelate enhanced the conversion of Cd from roots to shoots by 76%. (Zahedifar *et al.*, 2019). Wang, Jiang, et al. (2021) found that adding 500 mg kg^{-1} SiO_2-nanoparticles to rice shoots in an alternate wetting and drying irrigation system dramatically reduced arsenic by 29% and Cd by 68%. In contrast, when nano-SiO_2 was applied at the same rate in rice shoots under a continuous flooding system, the amount of Cd decreased by 50% and the amount decreased by 70%.

Furthermore, the application of nano-TiO_2 resulted in corresponding increases of 66%, 64%, 41%, 143%, and 46% for nutritional components like iron (Fe) in the upper plant parts, magnesium (Mg) in the taproots, and calcium (Ca), zinc (Zn), and potassium (K) in the underground plant parts (Wang *et al.*, 2021). Cadmium (Cd), lead (Pb), and copper (Cu) absorption in pakchoi was greatly decreased by nano-silica (SiO_2-SH) by 92.02%, 68.03%, and 76.34%, respectively, whereas in lettuce, absorption was decreased by 89.81%, 43.41%, and 5.76%, respectively. SiO_2-SH could change the acid-soluble forms of Cd, Pb, and Cu into reducible and oxidizable segments, preventing the heavy metals from being extracted from the soil, according to a study of their chemical forms. (Lian *et al.*, 2021).

8 Impact of nano fertilizers on seed germination

Numerous studies have demonstrated the beneficial effects of nano fertilizers on seed vigor by showing that they have a significant impact on seed germination and seedling growth. Because they can readily penetrate seeds, nano fertilizers make more nutrients available to developing seedlings, which leads to healthier seedlings with longer shoots and roots. However, there may be detrimental effects on seedling growth and germination if the concentration is higher than is ideal. For example, it has been reported that ZnO nanoparticles are harmful to garlic (Allium sativum L.) root growth (Nel *et al.*, 2006). Plants can be affected by nanoparticles in both positive and negative ways. When compared to bulk zinc sulphate, nano ZnO has been demonstrated to improve peanut seed germination and root growth. (Pijls *et al.*, 2009). SiO_2 and TiO_2 at the nanoscale have also been shown to improve soybean germination. When compared to control or non-nano fertilizer-treated seeds, higher seed germination, shoot length, and root length were noted under nano fertilizer treatment. By making nutrients more accessible to the developing plant, nano fertilizers accelerate the production of dry matter, chlorophyll, photosynthesis, and overall plant growth. According to studies, plants grown from seeds treated with nano-TiO_2 had higher dry weights, photosynthetic rates, and chlorophyll-a formation than plants grown from controls. According to these results, nano fertilizers greatly enhance plant growth and seed germination. (Prasad *et al.*, 2012).

9 Higher nutrient use efficiency in nano fertilizers.

Nano-fertilizers exhibit a higher surface area primarily due to their small particle size, which provides more sites for facilitating various metabolic processes within the plant system, thereby increasing the production of photosynthesis. The small particle size and high surface area also enhance their reactivity with other compounds. These nano-fertilizers also show excellent solubility in a variety of solvents, including water. Because nano-fertilizers usually have particle sizes smaller than 100 nm, they can more effectively enter plants through surfaces like soil or leaves (Lin & Xing, 2007). Nano-fertilizers can more readily enter plants because of their large surface area and particle size, which is smaller than the pore size of plant roots and leaves. This increases nutrient uptake and improves the efficiency of nutrient utilization. Because there are more particles per unit area and a higher specific surface area due to the reduction in particle size, there are more opportunities for contact, which improves nutrient penetration and uptake. (Liscano *et al.*, 2000).

The availability and uptake of nutrients by crop plants are improved by fertilizers encapsulated in nanoparticles. The ability of zeolite-based nano-fertilizers to release nutrients gradually guarantees a steady supply for crops during their growth period. This gradual release, especially for NO_3-N and NH_4-N, helps stop nutrient loss in the soil due to processes like denitrification, volatilization, leaching, and fixation. When applied as fertilizers, nanoparticles smaller than 100 nm can effectively manage nutrients, providing a more environmentally friendly option and lowering pollution levels in the environment. (Chinnamuttu & Kokiladevi, 2007). The main characteristics of nano-fertilizers that make them more appealing than their bulk counterparts are their size, penetration capacity, and noticeably larger surface area. The high surface-to-volume ratio of nanoparticles is partly to blame for this discrepancy. Because of this, nanoparticles have a proportionately larger reactive surface area than larger particles. The particle's surface area grows as its size decreases, and its size affects its surface free energy. Similar results have been documented in earlier research. (Lin & Xing, 2007).

10 Enhancement of plants' antioxidant defense system through nanofertilizers

Nanomaterials greatly lessen the negative consequences of outside stressors (El-Saadony *et al.,* 2021). According to Khalid et al. (2021), the application of nanoparticles (ZnO, FeO, and MgO) enhanced chlorophyll levels by 30% to 80% and improved plant morphological traits by 50% to 92%. It has been demonstrated that applying 200 ppm of nano-Zn to the foliage of stressed cotton crops improves their growth and productivity (Hussein & Abou-Baker, 2018). During the plant growth phase, SiO_2 spraying can increase the flexibility, firmness, and toughness of cell walls. (Yassen *et al.*, 2017). A study demonstrated that biological selenium nanoparticles inhibited fungal growth at concentrations between 20 and 40 mg/mL, significantly reducing DPPH$^{\bullet}$ and ABTS$^{\bullet}$ radicals by 88% and 92%, respectively. Under greenhouse conditions, wheat plants treated with 100 mg/mL of Bio-Se nanoparticles showed a marked reduction in the incidence of root and crown rot disease in wheat and a notable 5%–40% increase in plant growth, grain yield, and quality. Furthermore, there was a noticeable improvement in the gaseous exchange capacity and photosynthetic components (El-Saadony & Saad, *et al.*, 2021). Likewise, the chlorophyll content, carotenoids, transpiration rate, photosynthesis, stomatal conductance, membrane stability, total soluble sugars, nutrient uptake, and the activity of POD, CAT, SOD, and APX enzymes were all markedly enhanced by biological silicon nanoparticles. In addition, biological silicon nanoparticles decreased metals, $H2O_2$, O_2•−, MDA content, and electrolyte leakage in Phaseolus vulgaris L's aboveground sections and pods when compared to the control. (El-Saadony, & Desoky, *et al.*, 2021). When applied to Pb, Zn, Cd, and Cu solutions, nano-Fe3O4 particles up to 2000 mg/L reduced growth inhibition and activated defensive mechanisms in wheat plantlets, thereby reducing oxidative stress brought on by heavy metals. An increase in SOD and POD enzyme activity may be the cause of nano-Fe3O4's capacity to reduce mental stress. Their protective role was further reinforced by the decrease in MDA concentration (Konate *et al.*, 2017). Furthermore, by preserving the maximum photochemical efficiency of PSII (Fv/Fm), the maximum photo-oxidizable PSI (Pm), and photosynthetic gas exchange, NP amendments mitigated the negative effects of chilling stress. Additionally, sugarcane seedlings treated with NPs exhibited increased concentrations of substances that absorb light, including carotenoids and chlorophyll. The highest carotenoid content in the leaves treated with nanoparticles improved the non-photochemical quenching of PSII. (Elsheery *et al.*, 2020).

Conclusions

Recent research has shown that nano-fertilizers are extremely reactive and can enter plant cells through root hairs. Abiotic stress and heavy metal toxicity in plants can be lessened with the use of nanoparticles. Therefore, the technology of nanoparticles can be used in agriculture, specifically in the conversion of nanomaterials into nanoparticles and/or nano-fertilizers, which has the potential to improve agricultural productivity, cost-effectiveness, and carbon reduction. A major food safety concern is the build-up of heavy metals in plants, particularly for populations that eat staple foods like soybeans, rice, maize, and wheat. Metal ion translocation from roots to upper plant parts and from upper plant parts to rachises can be significantly decreased by nano-fertilizers. On the other hand, essential nutrients like K, Mg, and Fe can be more easily transferred from the higher plant parts to the rachises when using nano-fertilizers. As a result, nanoparticles can simultaneously raise antioxidant activity and the photosynthetic rate while lowering heavy metal levels and MDA activity. Nanotechnology may therefore present fresh opportunities for environmentally friendly agricultural production. Furthermore, nanoparticles have the ability to mimic plant defense mechanisms that scavenge reactive oxygen species, such as catalase, superoxide dismutase, and peroxidases. Therefore, the creation of green nanomaterials is useful, environmentally benign, and aids in lowering dependency on harmful substances.

References

Abdel-Aziz, H. M. M., Hasaneen, M. N. A. G., & Omer, A. M. (2018). Foliar application of nano chitosan NPK fertilizer improves the yield of wheat plants grown on two different soils. Egyptian Journal of Experimental Biology, 14, 63-72.

Ahmed, O. H., Hussin, A., Ahmad, H. M., Rahim, A. A., & Majid, N. M. A. (2008). Enhancing the Urea-N Use Efficiency in Maize (Zea mays) Cultivation on Acid Soils Amended with Zeolite and TSP. The scientific world journal, 8(1), 394-399.

Braun H. and Roy R. N. (1983) Proc. Symp. Efficient use of fertilizers in agriculture development in Plant and Soil Science, 10, 251-270.

Brunnert I., Wick P., Manserp., Spohnp., Grass R. N., Limbach L. K., Bruinink A. and Stark W. J. (2006) Environmental Science & Technology, 40, 4374-4381.

Chau, C. F., Wu, S. H., & Yen, G. C. (2007). The development of regulations for food nanotechnology. Trends in Food Science & Technology, 18(5), 269-280.

Chen, R., Zhang, C., Zhao, Y., Huang, Y., & Liu, Z. (2018). Foliar application with nanosilicon reduced cadmium accumulation in grains by inhibiting cadmium translocation in rice plants. Environmental Science and Pollution Research, 25, 2361-2368.

Chhipa, H., & Gupta, V. K. (2018). Nanofertilizers in agriculture: A review. Environmental Science and Pollution Research, 25(4), 3316-3336.

Chhipa, H., Gupta, A. K., & Sharma, R. (2023). Impact of nanoparticles on plants and its symbiotic microorganisms. In Nanoparticles and Plant-Microbe Interactions (pp. 369-387). Academic Press.

Chinnamuthu C.R. and Boopati, P.M. (2009) Nanotechnology and agroecosystem. Madras Agric. J. 96:17–31.

Chinnamuttu C. R. and Kokiladevi E. (2007) Weed management through nano-herbicides. In: Application of nanotechnology in agriculture.

Cui, H., Shi, Y., Zhou, J., Chu, H., Cang, L., & Zhou, D. (2018). Effect of different grain sizes of hydroxyapatite on soil heavy metal bioavailability and microbial community composition. Agriculture, Ecosystems and Environment, 267, 165-173.

Dwivedi, S., Saquib, Q., Al-Khedhairy, A. A., & Musarrat, J. (2016). Understanding the role of nanomaterials in agriculture. In Microbial inoculants in sustainable agricultural productivity (pp. 271-288). Springer.

El-Saadony, M. T., Saad, A. M., Najjar, A. A., Alzahrani, S. O., Alkhatib, F. M., Shafi, M. E., Selem, E., Desoky, E. S. M., Fouda, S. E., & El-Tahan, A. M. (2021). The use of biological selenium nanoparticles to suppress Triticum aestivum L. crown and root rot diseases induced by Fusarium species and improve yield under drought and heat stress. Saudi Journal of Biological Sciences, 28, 4461-4471.

Elsheery, N. I., Sunoj, V. S. J., Wen, Y., Zhu, J. J., Muralidharan, G., & Cao, K. F. (2020). Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photoprotection in sugarcane. Plant Physiology Biochemistry, 149, 50-60.

Ghaly A. E. (2009) American J. Biochem. Biotechnol, 5, 210-220.

Gutierrez, F.J., Mussons, M.L., Gaton, P. and Rojo R. (2011) Nanotechnology and Food Industry. Scientific, Health and Social Aspects of the Food Industry, In Tech, Croatia Book Chapter

Hamid R.B. (2012) Arpn J. of Agri. And Biological Sci., 7 (4), 233-237.

Hediat M.H. and Salama (2012) International Research Journal of Biotechnology, 3, 190-197.

Hussain, B., Lin, Q., Hamid, Y., Sanaullah, M., Di, Liu, Hashemi, M. L. R., Khan, M. B., He, Z., & Yang, X. (2020). Foliage application of selenium and silicon nanoparticles alleviates Cd and Pb toxicity in rice (Oryza sativa L.). Science of the Total Environment, 712, 136497.

Janmohammadi, M., Amanzadeh, T., Sabaghnia, N., & Dashti, S. (2016). Impact of foliar application of nano micronutrient fertilizers and titanium dioxide nanoparticles on the growth and yield components of barley under supplemental irrigation. Acta Agriculturae Slovenica, 107, 265-276.

Ji, Y., Zhou, Y., Ma, C., Feng, Y., Hao, Y., Rui, Y., Wu, W., Gui, X., Han, Y., Wang, Y., & Xing, B. (2017). Joined toxicity of TiO2 NPs and Cd to rice seedlings: NPs alleviated Cd toxicity and Cd promoted NPs uptake. Plant Physiology and Biochemistry, 110, 82-93.

Joseph, T., & Morrison, M. (2006). Nanotechnology in agriculture and food: a nanoforum report. Nanoforum. org.

Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. Nature nanotechnology, 14(6), 532-540.

Khalid, U., Sher, F., Noreen, S., Lima, E. C., Rasheed, T., Sehar, S., & Amami, R. (2022). Comparative effects of conventional and nano-enabled fertilizers on morphological and physiological attributes of Caesalpinia bonducella plants. Journal of the Saudi Society of Agricultural Sciences, 21(1), 61-72.

Konate, A., He, X., Zhang, Z., Ma, Y., Zhang, P., Alugongo, G. M., & Rui, Y. (2017). Magnetic (Fe3O4) nanoparticles reduce heavy metals uptake and mitigate their toxicity in wheat seedling. Sustainability, 9(5), 790.

Kottegoda, N., Munaweera, I., Madusanka, N., & Karunaratne, V. (2011). A green slow-release fertilizer composition based on urea-modified hydroxyapatite nanoparticles encapsulated wood. Current science, 73-78.

Kuzma, J. (2007). Moving forward responsibly: Oversight for the nanotechnology-biology interface. Journal of Nanoparticle Research, 9, 165-182.

Lian, M., Wang, L., Feng, Q., Niu, L., Zhao, Z., Wang, P., ... & Zhang, Z. (2021). Thiol-functionalized nano-silica for in-situ remediation of Pb, Cd, Cu contaminated soils and improving soil environment. Environmental Pollution, 280, 116879.

Lin, D., & Xing, B. (2007). Phytotoxicity of nanoparticles: inhibition of seed germination and root growth. Environmental pollution, 150(2), 243-250.

Liscano, J. F., Wilson, C. E., Norman-Jr, R. J., & Slaton, N. A. (2000). Zinc availability to rice from seven granular fertilizers (Vol. 963). Fayetteville, CA, USA: Arkansas Agricultural Experiment Station.

Liu, R., & Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the total environment, 514, 131-139.

Liu, X. M., Zhang, F. D., Zhang, S. Q., Feng, Z. B., He, X. S., Wang, Y. J., & Wang, R. F. (2005). Study on adsorption and desorption properties of nano-kaoline to nitrogen, phosphorus, potash and organic carbon. Scientia Agricultura Sinica, 38, 102-109.

Moraru, C. I., Panchapakesan, C. P., Huang, Q., Takhistov, P., Liu, S., & Kokini, J. L. (2003). Nanotechnology: a new frontier in food science.

Morteza, E., Moaveni, P., Farahani, H. A., & Kiyani, M. (2013). Study of photosynthetic pigments changes of maize (*Zea mays* L.) under nano TiO_2 spraying at various growth stages. Springer Plus, 2, 1-5.

Mukhopadhyay, S. S. (2014). Nanotechnology in agriculture: prospects and constraints. Nanotechnology, science and applications, 63-71.

Naderi M. R. and Abedi A. (2012) J. Nanotech., 11(1), 18-26.

Naderi, M., & Danesh-Shahraki, A. (2013). Nanofertilizers and their roles in sustainable agriculture. International Journal of Agriculture and Crop Sciences (IJACS), 5, 2229e2232.

Nair, R., Varghese, S.H., Nair, B.G., Maekawa, T., Yoshida, Y. and Kumar, D. S. (2010) Nanoparticulate material delivery to plants. Plant Sci. 179:154–163.

Nanotechnology in Agriculture, Scope and Current Relevance (2013) NAAS, New Delhi.

Nel, A., Xia, T., Madler, L., & Li, N. (2006). Toxic potential of materials at the nanolevel. science, 311(5761), 622-627.

Patil, V. C., 2009, Precision nutrient management: A review. Ind. J.Agron., 54 (2) :113-119.

Peng, C., Tong, H., Shen, C., Sun, L., Yuan, P., He, M., & Shi, J. (2020). Bioavailability and translocation of metal oxide nanoparticles in the soil-rice plant system. Science of the Total Environment, 713, 136662.

Pijls, L., Ashwell, M., & Lambert, J. (2009). EURRECA–a network of excellence to align European micronutrient recommendations. Food Chemistry, 113(3), 748-753.

Prasad, T. N. V. K. V., Sudhakar, P., Sreenivasulu, Y., Latha, P., Munaswamy, V., Reddy, K. R., ... & Pradeep, T. (2012). Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. Journal of plant nutrition, 35(6), 905-927.

Qureshi, A., D.K. Singh and Dwivedi, S. 2018. Nano-fertilizers: A Novel Way for Enhancing Nutrient Use Efficiency and Crop Productivity. Int.J.Curr.Microbiol.App.Sci. 7(02): 3325-3335.

Raliya, R., & Choudhury, A. (2017). Nanotechnology for sustainable agriculture: Nano-fertilizers and nano-pesticides. Environmental Chemistry Letters, 15(1), 1-9.

Renner, A., Cadillo-Benalcazar, J. J., Benini, L., & Giampietro, M. (2020). Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. Ecosystem Services, 46, 101195.

Rezaei, M., & Abbasi, H. (2014). Foliar application of nanochelate and non-nanochelate of zinc on plant resistance physiological processes in cotton (*Gossipium hirsutum* L.). Iranian Journal of Plant Physiology, 4(4), 1137-1144.

Roberts, T. L. (2008). Improving nutrient use efficiency. Turkish journal of agriculture and forestry, 32(3), 177-182.

Sahoo, U., Malik, G. C., Banerjee, M., Sahoo, B., & Maitra, S. (2022). Application of nanotechnology in agriculture in India. Int J Nat Sci, 13(72), 44422-9.

Scott, N. R. (2007). Nanoscience in veterinary medicine. Veterinary research communications, 31, 139-144.

Sebastian, A., Nangia, A., & Prasad, M. N. V. (2019). Cadmium and sodium adsorption properties of magnetite nanoparticles synthesized from *Hevea brasiliensis* Muell. Arg. bark: Relevance in amelioration of metal stress in rice. Journal of hazardous materials, 371, 261-272.

Shalaby, T. A., Bayoumi, Y., Abdalla, N., Taha, H., Alshaal, T., Shehata, S., ... & El-Ramady, H. (2016). Nanoparticles, soils, plants and sustainable agriculture. Nanoscience in food and agriculture 1, 283-312.

Siddiqui, M. H., Al-Whaibi, M. H., Faisal, M., & Al Sahli, A. A. (2014). Nano-silicon dioxide mitigates the adverse effects of salt stress on Cucurbita pepo L. Environmental toxicology and chemistry, 33(11), 2429-2437.

Subramanian, K. S., & Rahale, C. S. (2012). Ball milled nanosized zeolite loaded with zinc sulfate: a putative slow-release Zn fertilizer. International Journal of Innovative Horticulture, 1(1), 33-40.

Subramanian, K. S., & Thirunavukkarasu, M. (2017). Nano-fertilizers and nutrient transformations in soil. Nanoscience and plant–soil systems, 305-319.

Tarafdar J. C., Agarwal A., Raliya R., Kumar P., Burman U. and Kaul R. K. (2012b) Advanced Science, Engineering and Medicine, 4, 1-5.

Tewatia, R. K., 2012, Developments in fertiliser consumption in India. Ind. J. Agron., 57 (3): 116-122.

Wang, S., Wang, F., Gao, S., & Wang, X. (2016). Heavy metal accumulation in different rice cultivars as influenced by foliar application of nano-silicon. Water, Air, & Soil Pollution, 227, 1-13.

Wang, Y., Liu, Y., Zhan, W., Zheng, K., Lian, M., Zhang, C., ... & Li, T. (2020). Long-term stabilization of Cd in agricultural soil using mercapto-functionalized nano-silica (MPTS/nano-silica): A three-year field study. Ecotoxicology and Env. Safety, 197, 110600.

Wang, Z. L. (2000). Nanomaterials for nanoscience and nanotechnology. Characterization of nanophase materials, 1-11.

Yang, F., Hong, F., You, W., Liu, C., Gao, F., Wu, C., & Yang, P. (2006). Influence of nano-anatase TiO2 on the nitrogen metabolism of growing spinach. Biological Trace Element Research, 110, 179-190.

Yassen, A., Abdallah, E., Gaballah, M., & Zaghloul, S. (2017). Role of silicon dioxide nano fertilizer in mitigating salt stress on growth, yield and chemical composition of cucumber (Cucumis sativus L.). Int. J. Agric. Res, 22, 130-135.

Zahedifar, M., Es-Haghi, A., Zhiani, R., & Sadeghzadeh, S. M. (2019). Synthesis of benzimidazolones by immobilized gold nanoparticles on chitosan extracted from shrimp shells supported on fibrous phosphosilicate. RSC advances, 9(12), 6494-6501.

Zahra, Z., Habib, Z., Hyun, H., & Shahzad, H.M.A. (2022). Overview on recent developments in design, application & impacts of nanofertilizers in agriculture. Sustainability, 14(15), 9397.

Zhang, Y., et al. (2018). Nanotechnology in the field of agriculture: A review. Journal of Agricultural and Food Chemistry, 66(19), 5046-5059.

Zhou, J. M., & Huang, P. M. (2007). Kinetics of potassium release from illite as influenced by different phosphates. Geoderma, 138(3-4), 221-228.

Zhou, P., Adeel, M., Shakoor, N., Guo, M., Hao, Y., Azeem, I., ... & Rui, Y. (2020). Application of nanoparticles alleviates heavy metals stress and promotes plant growth: An overview. Nanomaterials, 11(1), 26.