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REVIEW

+Technological Advancement in the Development of Nano Fertilizers for Sustainable Agriculture

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Abstract

This review explores the significance of nano fertilizers in addressing the concerns associated with the indiscriminate application of chemical fertilizers in agricultural soil. It focuses on the need for crop and soil-specific fertilizer application to prevent nitrogen overuse and proposes nanomaterials as a viable solution for amending soil with plant nutrients. The review examines the potential of nanomaterials for soil nutrient enhancement and discusses the different techniques involved in synthesizing nanofertilizers. It emphasizes the importance of studying both macronutrients and micronutrients concerning plants and explores the effectiveness of applying nanoparticles through roots or leaf surfaces regarding plant absorption rates. The review highlights that nano fertilizers have effectively raised crop yields by providing the ideal and necessary nutrients. It discusses how nano fertilizers can alleviate the heavy burden of chemical fertilizers, reduce associated costs, and promote sustainable agriculture. In conclusion, the review suggests that nano fertilizers offer a promising alternative to traditional chemical fertilizers. Farmers can mitigate the negative impacts of excessive nitrogen use while boosting crop yields by applying nano fertilizers in a targeted and soil-specific manner. The findings indicate that nano fertilizers, created through various synthesis techniques, can contribute to sustainable agriculture by providing adequate plant nutrients and reducing the reliance on chemical fertilizers.

Keywords Nanomaterials · Nanoparticles · Plant nutrients · Nano-fertilizers · Fertilizer · Agriculture

1 Introduction

Midway through the twentieth century, Mexico and the Indian subcontinent were two developing nations where the green revolution was successfully implemented. The utilization of fertilizer for high-yielding cultivars the main emphasis of the Green Revolution because it was necessary at the time. However, to produce these new varieties, substantial amounts of chemical fertilizers and insecticides are required, necessitating the usage of chemical fertilizers in agricultural fields. The usage of chemical fertilizers regularly raises worries about environmental harm. No doubt, using chemical fertilizers help increase in productivity and meet the needs of the expanding population; excessive fertilizer consumption negatively impacts the environment and human health. The usage of agrochemicals harms living beings by contaminating soil and water worldwide.

On the other hand, when the population grows, crops should produce more as well. Chemical fertilizers are traditionally administered in considerable quantities to fields

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since they have issues with volatilization, leaching, denitrification, and fixation. The phrase "sustainable agriculture" explains the need to balance crop output and fertilizer use. Farmers must adopt modern farming techniques, including manure, biopesticides, nanofertilizers, and biofertilizers. The effectiveness of using fertilizers is unquestionably reduced by these modern technologies, which also improve the natural environment and the health of living things.

The usage of nanotechnology is one of the innovative solutions to these issues. Nano is defined as one billionth or 10^{-9} of anything. Nanomaterials are tiny molecules with sizes between one and one hundred nanometers. In contrast to their enormous size, these molecules exhibit various other physico-chemical characteristics. Due to their large surface-to-volume ratio, it has been shown that nanomaterials have improved physical, biological, and chemical characteristics (El-Saadony et al. 2021) . Many materials have been effectively utilized in several sectors up to this point. Nanomaterials made of titanium, gold, silver, copper, zinc, and carbon, among others, have already demonstrated their effectiveness in farming. They are applied as insecticides, herbicides, and fungicides to lessen plant stress. They control how plants absorb nutrients as well (Benelmekki 2015).

1.1 What are Nanofertilizers?

The usage of fertilizers in nano form is described by the term "nanofertilizer." Compared to traditional fertilizers, they are more effectively formulated. Nutrients may be delivered to the soil regulated and effectively using nanofertilizers. According to their needs, crops may absorb nutrients (Avila-Quezada et al. 2022).

Recently, research has focused on developing and exploiting fertilizer-related nanomaterials (NMs) to significantly increase agricultural output (Lal 2008; Jayakumar et al. 2010; Ghormade et al. 2011; Khot et al. 2012). NMs have received much interest because of their unique characteristics, small size, and less damaging and ecologically benign nature. Various physical, biological, and chemical methods (NPs) have produced nanoparticles (Kumar et al. 2018a, b; Ajish et al. 2020; Ahmed et al. 2021a, b). Primarily the nanoparticles can be used as a catalyst for various organic transformations and photodegradation reactions (Jadhav et al. 2022; Kanagare et al. 2022; Katariya et al. 2023; Bagade et al. 2023). The use of NPs (copper, zinc, iron, silver, gold, fungicides) to protect plants from different threats, promote plant growth and development, and treat biotic and abiotic problems has been emphasized in several studies that have demonstrated that NMs may have a role in agriculture. NMs reduced the excess production of ROS in plants by minimizing protein and nucleic acid damage from biotic and abiotic stimuli as well as cellular oxidative damage. Regulating nutrient absorption in harsh environmental situations also stabilizes plants' mineral intake.

Moreover, NMs in dry and semi-arid regions lead to reclamation inside the soil affected by salt stress (Singh and Husen 2019; Hassanisaadi et al. 2022). Furthermore, it has been discovered that using NMs for seed priming can improve the embryonic body by encouraging the germination processes and raising the seed germination ratio when the seed coat layer absorbs it and forms a water channel in the intercellular layer when environmental conditions are favourable. Nanomaterials are also used to develop biosensors to monitor changes in soil and plant diseases and stress. Various applications of nanofertilizers and their synthesis methods are summarized in Fig. 1.

1.2 Importance of Nanofertilizers

Several studies have shown that utilizing NMs may significantly increase plant growth and nutrient usage efficiency (Kah 2015; Ma et al. 2015; Ma et.al. 2018; Okey-Onyesolu et al. 2021). A few applications of NMs in the regulation of nutrient and agrochemical release have enabled the enhancement of the micronutrient supply (Ca, Mn, Fe, Cu, Zn, P, K, etc.) that further enhance plant development and biomass. Controlled release of agrochemicals increases the bioactivity of their active ingredients, which also raises the standard of the soil. It is emerging as a promising alternative strategy potentially transforming agricultural systems by supplying

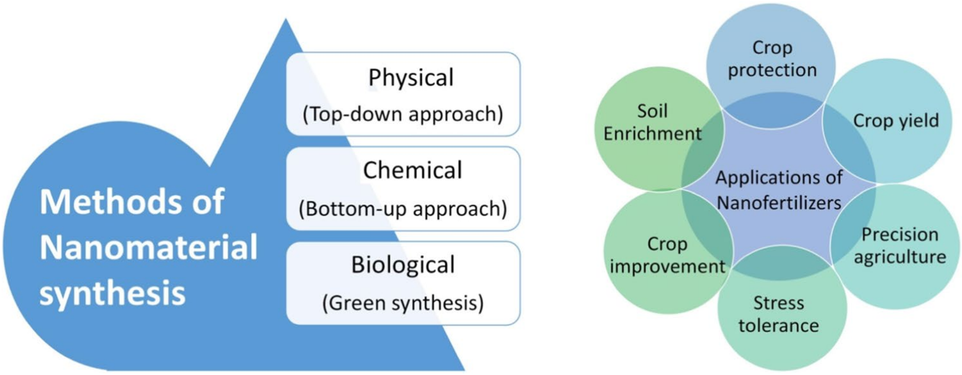

Fig. 1 Various synthesis methods and applications of nano fertilizers

nutrients to crops in a controlled release way. Engineering nanoparticle-based nano fertilizers improve crop nutrition management by increasing abiotic stress tolerance and increasing agricultural yield (Rashid Al-Mamun et al. 2021). Using nano fertilizers in agriculture is primarily intended to reduce mineral losses during fertilization, boost yields during mineral management, and stimulate agricultural growth (Thathsarani 2021). Nutrients, either alone or in combination, are attached to nano-dimensional adsorbents, which release nutrients much more slowly than traditional fertilizers (Zulfiqar et al. 2019).

Nanofertilizers (NFs) reduce fertilizer requirements in agriculture, improve nutrient uptake efficiency, and reduce fertilizer loss due to runoff and leaching. Furthermore, NFs have demonstrated encouraging outcomes in various plant species when employed in soil or foliar treatments. The main elements of nanomaterials include micro- and macronutrient precursors, as well as their nanoscale characteristics (Gade et al. 2023). A nanohybrid construct, such as nanofertilizers (NFs), is an excellent alternative to traditional chemical fertilizers. NFs provide innovative nitrogen delivery to plants and are more effective in agricultural productivity and environmental sustainability than bulky chemical fertilizers (Babu et al. 2022).

1.3 Market Size and Growth

The increased demand for food crops is driving a rapid expansion of the global market for nano fertilizers. In the coming five years, the global nano fertilizers market will grow due to the fast-increasing global population and the need to feed everyone. According to a recent market research report, the worldwide nano-fertilizers market was estimated to be USD 353.9 million in 2021 and is expected to grow at a noteworthy CAGR of 17.9% from 2022 to 2030. The expected market growth of the nanofertilizers industry by 2023 is depicted in Fig. 2 (https://www.precedenceresearch.com/nano-fertilizers-market).

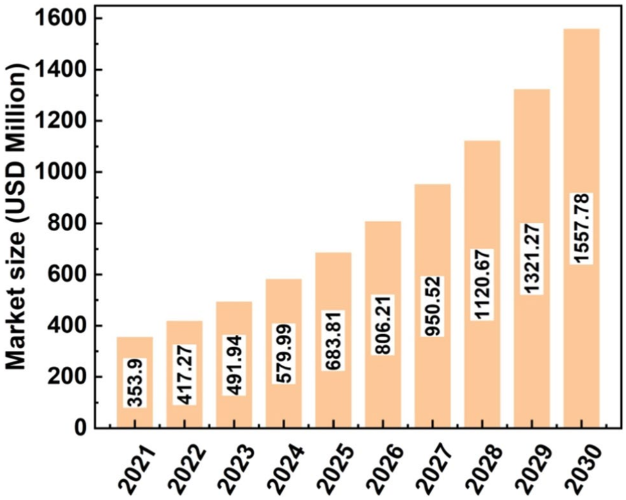

Fig. 2 Expected market growth of the nanofertilizers industry by 2023

2 Methods of Preparation of Nano Fertilizers

Nanofertilizer preparation involves nanoscale preparation of nutrient particles. This can be done by focusing on two approaches, which are bottom-up and top-down. The top-down approach includes using physical or chemical processes to convert bulk material into the nanoscale. The bottom-up approach involves the building of smaller materials to create nanoparticles. Chemical synthesis is a part of the bottom-up approach as it focuses on assembling particles at the atomic scale to create nanoparticles using chemical reactions. Biological methods are also gaining much interest due to their environmentally benign nature and cost-effectiveness of the technique. Various plant extracts, microorganisms, polysaccharides and biological macromolecules are used to synthesize nanomaterials by biological methods (Ali et al. 2020a, b; Samrot et al. 2020). Various methods of nanofertilizer preparations are discussed below.

2.1 Physical Processes: (Top to Bottom)

2.1.1 Gas Condensation

Gas condensation was the primary method used to create nanocrystalline metals and composites. Using thermal dissipation sources, such as Joule heated refractory crucibles and electron beam evaporation apparatus, a metallic or inorganic substance is evaporated in a 1 to 50 m bar atmosphere. During gas evaporation, ultrafine particles (100 nm) are arranged by gas stage collision, which generates high residual gas pressure. The gas condensation process is incredibly sluggish (Rajput 2015). In the experimental studies conducted by Nekrasova et al. (2011), *Elodea densa* Planch. Plants were treated in two different copper-containing solutions: copper sulfate dissolved in water and a suspension of copper oxide nanoparticles that were synthesized using the gas phase method. The nanoparticles had a size of approximately 30 nm and were found to be composed of 70% CuO and 30% Cu_2O based on X-ray analysis results. The nanoparticles showed increased lipid peroxidation, catalase and superoxide dismutase activities (Nekrasova et al. 2011).

2.1.2 A High Energy Ball Mill

One of the easiest methods to produce several metals and alloys' nanoparticles a ball mill with high energy is utilized. This process uses various mill types, like planetary, tumbler, rod, vibratory, etc. There are one or more containers used to produce fine particles. Balls made of tungsten carbide or hardened steel are kept in containers with powder or flakes (less than 50 µm) of the material. The container is typically sealed with a tight lid. 2:1 is typically a good ratio for balls to substance. If a container is filled to more than half its capacity, milling efficiency is diminished. If larger balls are utilized for milling, the grain size will be smaller and the particles will have more flaws. The ball can contribute pollutants throughout the process, or the container might be stuffed with air and inert gas. During a collision, temperatures rise by 100 to 1100 °C. This process produces nanocrystalline cobalt (Co), chromium (Cr), tungsten (W), and other metals (Maissel 1971).

2.1.3 Laser Ablation

A method for creating nanoparticles by irradiating a target substance with a laser in a liquid environment is known as laser ablation synthesis. During the procedure, the laser beam vaporizes the target material, creating a plasma plume that quickly cools and condenses to produce nanoparticles. By changing the laser's pulse duration, energy density, and wavelength, one may alter the size and shape of the nanoparticles. With the advantage of manufacturing high-purity nanoparticles without the need for extra chemical or physical treatments, this technique is frequently used to synthesize a variety of nanoparticles, including metals, oxides, and semiconductors.

Singh et al. (2013) conducted a study on synthesizing ZnO nanoparticles using laser irradiation. The process involved placing a piece of 99% pure Zn metal in distilled water and irradiating it with a focused pulse Nd: YAG laser beam. This produced zinc plasmas and hydroxy ions from water at a solid–liquid interface, forming zinc hydroxide crystals that decomposed into ZnO particles. The ablation process was carried out for a specific duration to maintain the colloidal nature of the nanoparticles and prevent their sedimentation or aggregation. The authors observed that the synthesized ZnO nanoparticles positively affected germination, seedling growth, chlorophyll content, and antioxidant system of cabbage, cauliflower, and tomato vegetable crops. The nanoparticles could reduce the phytotoxic effects of bulk ZnO. These results suggest that ZnO nanoparticles produced by laser irradiation may be used to promote plant development and lessen the harmful effects of ZnO (Singh et al. 2013). In addition to synthesizing ZnO nanoparticles through laser ablation, the authors also applied this technique to produce TiO_2 nanoparticles for use as nanofertilizers. The method for synthesizing TiO_2 nanoparticles was similar to the manner described above for ZnO synthesis, except that a Ti rod was used as the target material instead of Zn metal. The laser ablation process generated a plasma plume that condensed to form TiO_2 nanoparticles, which could be used to enhance plant growth as a nanofertilizer (Singh et al. 2012).

2.1.4 Aerosols Synthesis Method

Five different aerosol processes are utilized to create nanoparticles, including the boiler method, flame method, electro spray, physical method of vapour deposition, and chemical vapour deposition method. By employing the boiler method, producing particles smaller than 100 nm is exceedingly challenging. With adequate safety measures, the flame process may successfully generate TiO_2 nanoparticles. Using the effective Electro-spray approach, precise nanoparticle size and shape may be created, although with a minimal yield of approximately (1 g per year). Chemical vapour deposition and physical vapour deposition are effective ways of producing nanoparticles. By carefully regulating the heater size, gas flow rate, and diffusion dryer size, NPs are produced via the aerosol process. Cube, plate, cage, and wire-shaped nanoparticles are some of the different shapes that can be assigned to them (Raliya and Tarafdar 2013).

2.1.5 Thermolysis Method

This technique produces nanoparticles from organometallic precursors most effectively. The disintegration of organometallic precursors should be susceptible to the effects of heat (thermolysis), sound (sonolysis), or light (photolysis). The fundamental advantage of organometallic combinations is separating the precursors and generating the required product at equally low temperatures. Simple hosts, polymers, and organic topping agents are frequently used to limit the growth of nanoparticle (Palacios-Hernández et al. 2012).

2.2 Chemical Processes: (Bottom to Top)

2.2.1 Chemical Precipitation Method

Precipitation is the most efficient, easy and inexpensive nanoparticle synthesis approach. A pure stoichiometric chemical with an excellent crystal and particle-size distribution may be produced using this technique (Dumrongrojthanath et al. 2021). A chemical precipitation process consists of three key stages: chemical reaction, nucleation, and crystal growth. Chemical precipitation is frequently an uncontrolled pathway regarding reaction kinetics, solid phase nucleation, and growth processes. This results in various molecule sizes, random particle morphologies, and agglomeration solids during chemical precipitation (Nalwa 1999). Using different templates and capping agents has helped control the size and aggregation of the nanoparticles in previous reports (Thirumavalavan et al. 2013).

Hydroxyapatite nanoparticles were synthesized by dropwise addition of orthophosphoric acid in the measured concentration and volume of the $Ca(OH)_2$ under constant stirring. The obtained milky solution was kept in a refrigerator for 24 h to get precipitated hydroxyapatite nanoparticles. The following describes the chemical reaction that occurs:

$$6H_3PO_4 + 10Ca(OH)_2 \rightarrow 10Ca(PO_4)_6(OH)_2 + 18H_2O$$

Hydroxyapatite nanoparticles were then subjected to modification with urea to improve their efficacy. A formulation of urea-modified hydroxyapatite and various copper, iron, and zinc nanoparticles was prepared and tested on the *Abelmoschus esculentus plant* for enhancement in the Cu^{2+}, Fe^{2+}, and Zn^{2+} nutrient uptake (Tarafder et al. 2020). Fahad et al. (2022) synthesized Fe_3O_4 nanoparticles by chemical precipitation and found their ability to mitigate the toxicity of cadmium and lead toxicity in coriander plants. To synthesize Fe_3O_4 nanoparticles, the mixture of ferric and ferrous chloride in a 2:1 ratio was heated at 80 °C in a round bottom flask for 20 min. Then, Fe_3O_4 nanoparticles were precipitated by immediately adding the appropriate volume of NH_4OH to the above solution and cooling the solution to room temperature for hrs. The pH of the solution was brought to neutral by repeatedly washing the precipitate with deionized water (Fahad et al. 2022). A simple green precipitation technique was employed to obtain multi-nutrient (NPK) riched calcium phosphate nano fertilizers using citrate and carbonate ions as reducing agents. The experimental conditions were tuned to dope an appropriate quantity of the urea and nitrate for their control-led release, thus improving fertilizers' efficiency (Ramírez-Rodríguez et al. 2020). Jahangirian et al. (2020) synthesized Zeolite/Fe_2O_3 nanocomposite by the co-precipitation method and could achieve a controlled release of iron ions. The cytotoxicity studies showed that the nanofertilizer is non-toxic and thus can be used as fertilizer to enhance crop yield without any hazardous effects (Jahangirian et al. 2020).Zn-urea nanofertilizers were developed by Dimkpa et al. (2022) for nutrient delivery applications in wheat. The chemical precipitation technique was employed to synthesize the ZnO nanoparticles using a combination of capping agents. The dual-capped ZnO nanoparticles coated on the urea granules facilitated nanoscale fertilization delivery to the plant (Raliya et al. 2018).

2.2.2 Sol–Gel Techniques

For this technique, low temperatures are frequently employed. Some materials that utilize the sol–gel method include zeolites, aerogels, and solids with pores formed through inorganic–organic hybridization. Using the sol–gel method, nanoparticles, nanotubes, and nanorods may all be created. This procedure builds a network by creating a liquid called "sol" and then joining the sol particles. Thin films and even massive solids may be produced by drying liquid powders. As a result of this process, ceramics, metal oxides, sulphides, borides, and nitrides are produced (Jones 1989). Lower operational cost, process ease with reliability, and reproducibility are advantages of the sol–gel technology. Various combinations of nanomaterials have been synthesized using sol–gel technology, especially for nanofertilizer applications. Some of the recent work has been discussed herewith. Khalid et al. (2022) prepared MgO NPs nanofertilizers by sol–gel method and compared its efficacy in crop improvement with conventional fertilizers.

To prepare MgO nanoparticles, $Mg(OH)_2$ sol was prepared by mixing appropriate molar concentrations of $MgCl_2$ and NaOH under continuous stirring for 4 h. The obtained sol was then separated by centrifugation and washed several times with deionized water. The residue was then dried in an oven at 60 °C for 24 h and then calcined at 450 °C for 2 h to obtain MgO nanoparticles (Khalid et al. 2022). In another report, Silica particles containing Ca, P, Cu or Zn ions were synthesized using the sol–gel method and evaluated their effect on foliar fertilization. To prepare micronutrient-loaded SiO_2 particles, Tetraethoxysilane (TEOS) was dispersed in a mixture of water and ethanol and was added with a small amount of HNO_3 under continuous stirring. The obtained sol was added to the TEOS solution prepared in the ethanol and water mixture and ammonia. The precursors of the micronutrient were dissolved in water, added to the above-prepared sol, and stirred for 24 h. The precipitate was washed with deionized water thrice and the residue obtained was dried and then calcined at 700 °C for 2 h to obtain the nanofertilizer (Borak et al. 2023).

2.2.3 Chemical Vapor Deposition

In CVD, reactants are converted into microcrystalline and powder products in the vapour phase, and single crystal films for devices are then created via deposition on a substrate. Vapours are created by heating the flammable starting components; they are combined at an appropriate temperature and transferred to the substrate by a carrier gas. The typical starting material contains volatile chemicals like hydrides, halides, and organometallic compounds. The MOCVD (Metal Organic Chemical Vapor Deposition) method utilizes organometallic as a precursor. Removing them from the substrate transfers the by-products to the gaseous phase (Milani and Iannotta 2012). Kumar et al. (2018a, b) synthesized PVA–starch-based polymeric formulation and used it as a substrate for the slow release of the Cu–Zn micronutrient-carrying carbon nanofibers (CNFs). Carbon Nanofibers (CNFs) were synthesized on the Cu–Zn/ activated carbon fibre (ACF) by Chemical vapour deposition (CVD). Cu–Zn/CNFs were then dispersed in the polymer blend of PVA-starch in situ during the polymerization process. The biopolymer blend is biodegradable and slowly releases micronutrients carrying CNFs, showing significant crop improvement in chickpeas, a model plant (Kumar et al. 2018a, b). Yatim et al. (2018) studied the effect of functionalized Carbon nanotubes-urea fertilizer (CNT-UF) on paddy growth and found significant growth enhancement and grain yield for functionalized CNT-UF. Multi-walled CNT (MWCNT) was synthesized using the CVD method to prepare nanofertilizer. Bare MWCNTs and carboxy (-COOH) group functionalized MWCNTs were sonicated for the appropriate time to get uniform dispersion, stirred with urea fertilizer for 6 h at room temperature, and dried at 70 °C to obtain MWCNT grafted on urea fertilizer (Yatim et al. 2018).

2.2.4 Hydrothermal Synthesis

Hydrothermal synthesis is a method of synthesizing nanoparticles using high temperature and pressure in an aqueous solution. A precursor solution containing the metal ions or other desirable components to be synthesized into nanoparticles is heated under pressure in an autoclave or enclosed container to promote the nucleation and growth of nanoparticles (Gan et al. 2020). High pressure and temperature during the hydrothermal process provide a supercritical environment that promotes the production of nanoparticles with precise control over their size, shape, and content (Caramazana et al. 2018). By modifying the reaction's temperature, pressure, pH, and precursor solution concentration, one may alter the size and shape of the nanoparticles. It is possible to create nanoparticles with excellent purity, a uniform size distribution, and high crystallinity using the hydrothermal technique of nanoparticle synthesis. Additionally, it is an adaptable technique that may be used to create various materials, such as metals, metal oxides, and semiconductors. The hydrothermally synthesized Mn_3O_4, ZnO, and Fe_2O_3 have shown promising application as a nanofertilizer, improving the growth, yield, and quality of the *Cucurbita pepo L.* plant. A series of aqueous precursor solutions for various metal oxides were prepared and the pH of these solutions was adjusted to pH 11. The prepared precursor solutions were then transferred to a Teflon autoclave. The autoclave was subjected to microwave irradiation using a 750 W advanced microwave synthesis lab station, with the temperature adjusted to reach the desired level in 3 min. The reaction temperature was then maintained at a constant level for 10 min to ensure the complete conversion of the precursor solution to the corresponding metal oxide (Shebl et al. 2019). In another report, authors synthesized manganese zinc ferrite nanoparticles via a similar method and found significant growth and yield enhancement in squash plants (Shebl et al. 2020). This synthesis method utilizes microwave irradiation to generate heat rapidly and efficiently, which promotes the formation of metal oxides from the precursor solutions. Using a Teflon autoclave allows the reaction to occur under high pressure, further enhancing the synthesis of the desired metal oxides. Adjusting the pH to 11 ensures the stability of the precursor solution and facilitates the formation of the metal oxide nanoparticles.

2.2.5 Photochemical Method

Photochemical processes induced by the absorption of photoenergy can result in structural changes in molecules. Low-pressure mercury lamps are commonly used for UV irradiation, while high-pressure indium column lamps are often employed for visible light photoirradiation. This method offers the advantage of operating under mild reaction conditions, and the equipment involved is simple and cost-effective (Dong et al. 2004).

2.2.6 Gamma–Radiation Technique

Gamma radiation is a modern and effective technique for creating materials with nanometer dimensions. This method has been widely applied to produce nanocrystalline metals, oxides, polymer, and alloy nanocomposites. Inorganic and organic composites are a crucial focus in numerous applications and research fields, particularly semiconductive chalcogenides/polymer nanocomposites. Polymer/inorganic nanocomposites can be synthesized by simultaneously polymerizing monomers and inducing the structuring of inorganic nanoparticles using gamma radiation. Additionally, gamma irradiation is a well-known method for producing chalcogenide/polymer nanocomposites. This technique enables the creation of effective nanoparticles and allows for investigating the correlation between their structure and properties (Dong et al. 2004).

El-tanahy et al. (2022) reported the synthesis of potassium and iron oxide nanoparticles using polyvinyl alcohol (PVA) and polyvinylpyrrolidone (PVP), respectively as a capping agent under gamma irradiation. The PVA-capped potassium nanoparticles were prepared as follows. The PVA solution was prepared in double distilled water at 80 °C, and a suitable amount of acetic acid and ethanol was added. Then, potassium sulfate salt was added to the solution, which was exposed to gamma radiation at the optimum dose. This resulted in the formation of potassium and iron oxide nanoparticles, which were characterized using various techniques. To prepare PVP-stabilized iron oxide nanoparticles, a reaction mixture containing optimum concentrations of PVP, glycerol and iron sulfate was exposed to gamma irradiation as described above for the potassium nanoparticles. Using PVA and PVP as a capping agent and gamma irradiation as a synthesis method provides a simple and effective approach for producing nanoparticles with potential applications to enhance crop growth and productivity (El-tanahy et al. 2022). The gamma irradiation method was also employed to synthesize silver nanoparticles (AgNPs) and biological and chemical stabilizing agents. The supernatant from the different fungal strains was mixed with the appropriate quantity of silver nitrate ($AgNO_3$) and exposed to gamma radiation at a dose rate of 2.9 kGy/hr to obtain AgNPs. Synthesized AgNPs showed significant enhancement of disease resistance of crops towards the plant pathogens. The foliar application of AgNPs synthesized by gamma irradiation also showed increased crop growth and various physiological parameters (El-Batal et al. 2016).

2.3 Biological

2.3.1 Nanofertilizer Synthesis by Using Microbes

Micro-organisms contain different types of reductase enzymes which act as reducing agents in nanoparticle synthesis (Singh et al. 2016).

By Using Bacteria Different cyanobacteria are used to synthesize metallic nanoparticles, which can be used as nanofertilizers (Pathak et al. 2019). In another case, *Streptomyces sp.* was used to synthesize TiO_2 nanoparticles. To synthesize TiO_2 nanoparticles, a loopful culture of bacteria was inoculated in 20 ml of the nutrient broth and incubated for 24 h in a shaker incubator. It was then added with the appropriate $Ti(OH)_2$ quantity and further incubated in a steam bath at 60 °C for 30 min. After incubation, it was discovered that the culture fluid had left behind clearly distinguishable coalescent white clusters at the base of the flask. The precipitate was produced by centrifugation, and the pH was kept neutral by washing with distilled water (Ağçeli et al. 2020). Ameen et al. 2020 synthesized silver nanoparticles using the soil bacteria *Cupriavidus* sp. After 24 h of incubation in a shaker incubator, bacterial cells were separated by centrifugation, and the supernatant was used for the extracellular synthesis of silver nanoparticles (AgNPs). The cell supernatant was stirred with a 1 mM concentration of $AgNO_3$ until the concordant's colour change was observed, indicating successful AgNPs synthesis (Ameen et al. 2020). In another study. *Pseudomonas fluorescens* MAL2 copper-resistant bacteria strain was used to synthesize copper nanoparticles (CuNPs) (El-Saadony et al. 2020). *Escherichia coli, Exiguobacterium aurantiacumm,* and *Brevundimonas diminuta* were used for the synthesis of silver nanoparticles by Saeed et al. (2020).

By Using Fungi Nanoparticle synthesis using fungal culture is more convenient than bacterial synthesis as it produces various reducing enzymes in larger amounts (Ovais et al. 2018). *Aspergillus, Fusarium, Penicillium, Trichoderma, Talaromyces, Rhizopus, Pichia* were used to prepare different MNPs (Jeevanandam et al. 2016).

2.3.2 By Using Plants

Metallic nanoparticles can be synthesized by using different plant-part extracts. Plant parts such as the stems, leaves, roots, flowers, and fruits can be utilized to synthesize metallic nanoparticles (Rajeshkumar and Bharath 2017; Solgi and Taghizadeh 2020). Zn, Mn, and Fe nanoparticles were synthesized using an extract derived from *Vaccinium myrtillus* (Murgueitio-Herrera et al. 2022). Molybdenum nanoparticles were prepared by using *Cicer arietinum* extract (Taran et al. 2014). While *Oryza sativa* leaf extracts can synthesize Magnese nanoparticles (Raj and Subramanian 2014). Many plants played a significant role in producing Ag, Cu and Au metallic nanoparticles. *Medicago sativa, Aloe vera, Azadirachta indica, Avena sativa, wheat, Tamarindus indica, lemongrass, Emblica officinalis, Humuluslipulus, Spinacia oleracea, Lactuca sativa, Capsicum annum, Brassica juncea, Helianthus annus* are few plants which able to synthesize metallic nanoparticles (Gardea-Torresday et al. 2002; Chandran et al. 2006; Shankar et al. 2003a, b, 2004; Armendariz et al. 2004a, b; Ankamwar et al. 2005a, b; ShivShankar et al. 2005; Rai et al. 2006; Kanchana et al. 2011; Jha and Prasad 2011; Marchiol 2012). The Biogenic NPs have been found to exert a notable influence on various aspects of seed germination, including the rate of germination, the germination speed index, and the growth and development of both the stem and root systems. In addition to photosynthetic pigments, the analysis includes measuring total protein content, enzyme activity, phenolic compound concentration, and total soluble sugar levels (Salih et al. 2022).

3 Macronutrient Nanofertilizer

To boost plant output, macronutrient fertilizers have been utilized extensively. The macronutrients N, P, K, Mg, S, and Ca are thought to be essential for plant growth. Huge quantities of these synthetic fertilizers are used on the field, but because they are ineffective, most of the nutrients end up in the groundwater bodies. These nutrients subsequently have an impact on the ecosystem of the water body, which eventually has an impact on people and aquatic life. The usage of macronutrient nanofertilizers is recommended to solve all of these issues.

3.1 Carbon Nanofertilizer

Nitrogen and phosphorus utilization efficiency was improved due to the application of nanocarbon in *Brassica juncea var. tumida* (Wang et al. 2018). Nanocarbon synergist, along with compound fertilizer, was used for treatments of a wheat field. These treatments improved nitrogen utilization in wheat plants (Yang et al. 2023).

3.2 Nitrogen Nanofertilizer

Nitrogen nanofertilizer was used by Kumar et al. (2022) in the field of wheat, pearl millet, mustard and sesame. The nanofertilizer application was done along with the biofertilizer consortium. Higher yields of wheat, sesame, pearl millet, and mustard were seen after application compared to chemical fertilizers at 5.35%, 24.24%, 4.02%, and 8.4%, respectively (Kumar et al. 2022).

3.3 Phosphorus Nano Fertilizer

Hydroxyapatite ($Ca_5(PO_4)_3OH$) nanofertilizer was synthesized and its effect on soybean by Liu and Lal (2014). A greenhouse experiment with an inert medium was done to know the effect on plant growth. It was observed that seed yield and the growth rate increased by 20% and 33% compared to usual fertilizer use. Both above- and below-ground biomass grew by 18% and 41%, respectively. The use of phosphorus nanofertilizer can enhance yield as well as reduce the leaching effect.

Nano rock phosphate was applied in a maize field by Adhikari et al. (2014), where they got positive results similar to the application of superphosphate. Rock phosphate also costs less compared to superphosphate. Using a controlled amount of phosphorus nanofertilizer helps to increase the crop's biological functions due to increased uptake of P (Tiessen 2008; Priyam et al. 2022). Conventional fertilizers and phosphorus nanofertilizers were applied to *Ipomoea aquatica* (Kalmi), and results showed that the plant's P uptake and concentration were higher than the use of CFs (Rajonee et al. 2017). Nano-zeolite-P proved to be useful in peanut crops as it increased crop productivity after application (Hagab et al. 2018).

The physiology of roots and shoots of rice was efficiently increased when phosphorus nanofertilizer was applied. Slow-release phosphorus nanofertilizer was applied to tomato crops in a variety of soil. It was observed that phosphorus level was increased in tomato crops along with germination and growth enhancement. When phosphorus nano fertilizer was applied to rice plants, greater physiological efficiency in shoots and roots was observed. Water use efficiency was also increased in rice plants after the application of phosphorus nanofertilizer. The phosphorus dosage requirement was reduced to 50% in rice plants due to using phosphorus nanofertilizer (Reis et al. 2022).

Compared to traditional phosphorus fertilizer, 5% growth enhancement and 30% dry yield enhancement was observed in cluster bean when nHAP was applied (Shylaja et al. 2022). Higher phosphorus content was obtained in the lettuce plant after applying phosphorus nanofertilizer (Taşkın et al. 2018). Zeolite was incorporated with phosphorus nano fertilizer and applied to spinach. Two times higher accumulation of phosphorus and potassium was observed in spinach plants. Also, positive effects were observed in the soil after the application (Rajonee et al. 2017). Mikhak et al. gave different treatments of saturated nano zeolite with ammonium sulfate to chamomile (*Matricaria chamomilla* L.) and found significant crop enhancement (Mikhak et al. 2017). Final results reveal that nCp/nHA can be used as a substitute for regular fertilizer as they significantly increase yield and help minimize eutrophication risk.

3.4 Potassium Nanofertilizer

Potassium nanoparticle with different concentrations was used to evaluate the physiological effect in green beans cv. 'Strike'. After evaluation, it was found that foliar application of potassium nanofertilizer positively impacted plant growth, yield, nitrate reductase, and photosynthetic activity (Márquez-prieto et al. 2022). According to Noaema and Alhasany 2020, wheat's chlorophyll content and growth increased when potassium nanoparticles were sprayed on it. Another study was done on the effect of foliar spray of potassium nanofertilizer on maize (Beeresha and Jayadeva 2020).

Nanopotassium fertilizer treatment was given to the eggplant. Plant height, leaf number, leaf area, chlorophyll, dry weight, and eggplant leaf content were higher when compared with regular potassium fertilizer (Al-Fahdawi and Allawi 2019). Rice crops were sprayed with conventional potassium fertilizer and nanofertilizer. Results showed the highest grain yield in rice plants that are sprayed with nanopotassium (Ali et al. 2020a, b). According to the study of Seyed et al. nanopotassium application to rice varieties can enhance rice quality (SadatiValojai et al. 2021).

3.5 Calcium Nanofertilizer

Xiumei et al. applied Ca nano fertilizers to *Arachis hypogea* seedlings with Hoagland solutions and observed improved seedling growth compared to the control (Xiumei et al. 2005). They also used Ca- NP along with humic and achieved maximum seedling growth. According to the research of foliar application of CaO nanofertilizer improved Ca accumulation and root development in Ca-deficient peanut plants as compared to regular $CaNO_3$ and CaO treatment (Deepa et al. 2015).

Increased root and shoot growth and much biomass production were observed in the Mung plant when $CaCO_3$ nanoparticles were applied (Yugandhar and Savithramma 2013). One of the studies was done by Rane et al. (2015) on *Zea mays*, where they treated maize plants with endosymbiont (*P. indica*) and arbuscular mycorrhizal fungus (*G. mosseae*) and calcium phosphate nanoparticles (CaPNPs). After evaluation, enhanced growth and vitality were observed in maize plants. Rice plant growth and the antioxidant response were found to be dependent on the dose of $Ca_3(PO_4)_3$ NPs (Upadhyaya et al. 2017).

Urea-doped $Ca_3(PO_4)_3$ NPs application to grapevine fields showed an increase in yield and quality of grapes as compared to the treatment of conventional fertilizers (Gaiotti et al. 2021) Different nano-calcium and urea combinations were applied to cucumber plants (Alyasiri and Bhiah 2021). The increased plant height, the total number of leaves, and the average leaf area of the cucumber plant were observed.

3.6 Sulphur Nano Fertilizer

Yuan et al. (2021) induced mercury stress in *Brassica napus* L. and observed the effect of sulphur nanoparticles on it (Yuan et al. 2021). They recorded that sulphur nanoparticles significantly decreased mercury accumulation and toxicity, enhancing biomass and nutrient accumulation. Salem et al. (2016a) synthesized SNPs and used them for the treatment of tomatoes. Their study reported enhancement in the shoot and root length of tomato plants. The rate of enhancement was dependent on the concentration of doses. Green synthesized sulphur nanoparticles were applied to *Cucurbita pepo,* and *Cucumis sativus* seeds and increased germination percentages were observed (Albanna et al. 2016; Salem et al. 2016b).

3.7 Magnesium Nano Fertilizer

Vigna unguiculata was used as test plant by Delfani et al. They applied Mg NP as a foliar on a plant with a mixture of half a gram per litre of Fe -NP and Mg -NP. They noticed that this application increased the weight of 1000 seeds by 7%, which was also more than the regular application of Fe and Mg. According to researchers foliar applications of Mg and Fe elements helped to increase the plant's photosynthetic efficiency (Delfani et al. 2014).

3.8 Polymer Nanoparticles

The study conducted by Xin et al. (2020) examined the impact of recently developed poly succinimide nanoparticles (PSI-NPs) on the germination of maize (*Zea mays L.*) seeds and subsequent growth of seedlings under varying levels of copper (Cu) stress. The study's findings indicated that the PSI-NPs had an impact on the seed germination process, and this effect was observed to be dependent on the dosage of PSI-NPs administered. The most favourable rate of PSI-NPs for promoting seed germination was determined to be 200 mg L^{-1}. Furthermore, a positive correlation ($r=0.82$) was observed between the positive impacts of PSI-NPs on seed germination parameters and the enhancement of seed imbibition. The inclusion of PSI-NPs demonstrated a notable reduction in Cu stress, as seen by enhanced shoot and root growth, as well as increased activity of antioxidant enzymes when PSI-NPs were administered alongside Cu stress therapy, compared to treatment with Cu stress alone (Xin et al. 2020).

4 Micronutrient Nano Fertilizer

4.1 Zinc Nanofertilzer

Zn nanoparticles were studied for their contribution to plant growth by various researchers. In one of the studies done by Lin and Xing (2007), Radish (*Raphanus sativus*) and rape (Brassica napus) seeds that have germinated longer roots than the control seeds were observed after the use of Ryegrass (*Lolium perenne*) seedling growth was accelerated by 2 mg L^{-1} of ZnO-NPs and 2 mg L^{-1} of metallic Zn nanoparticles. A low concentration of Zinc nanoparticles can enhance growth in mung beans and chickpeas, according to a study by Mahajan et al. (2011). Another research was done by Zhao et al. 2013 on cucumber plants in a greenhouse. 400 and 800 mg/kg of ZnO nanoparticles were used in a soil mixture, and an increase in growth. Further quantitative analysis of starch, glutelin and Zn in cucumber fruits showed increased contents (Zhao et al. 2014).

The activity of phosphatase and phytase activity and 11% P uptake increased in legumes and cereals when ZnO nanoparticles were applied (Raliya and Tarafdar 2013). Nutritional value, yield, biomass and plant growth were enhanced in cereals and legumes after applying ZnO nanoparticles (Raliya et al. 2018). ZnO nanoparticles mixed with growth substances and treatment were given to *Triticum aestivum* by Du et al. (2019). They noticed higher *Triticum aestivum* grain output and biomass buildup increased net photosynthetic rate and biomass buildup was observed in *Coffea Arabica* when ZnO nanoparticles were used as foliar spray (Rossi et al. 2019).

Combined treatment of phosphorus supplements and ZnO nanoparticles were given to cotton plants, and results were observed. Results showed an increase in plant growth-promoting activity (Venkatachalam et al. 2017). A similar type of combination was also used by Vallee and Falchuk, where they found an increase in biomass, protein quantity and photosynthetic pigments (Vallee and Falchuk 1993). In recent studies, *Coriandrum sativum* leaf extract was used to synthesize ZnO NPs with particle size of 78 to 84 nm. These ZnO NPs were found to boost protein and chlorophyll levels and seed germination in pulses such as Bengal Gram, Turkish Gram, and Green Gram (Ukidave and Ingale 2022).

4.2 Manganese Nano Fertilizer

Pradhan et al. (2013) studied mung bean (*Vigna radiata*). They used magnese nanoparticles and Magnese sulphate for the treatment of mung bean. They observed enhanced growth in mung beans which were treated with magnese nanoparticles as compared with magnese salts (Noman et al. 2023). Manganese NPs were used in crop disease management recently by Noman et al. 2023 in watermelon plants. The mitigation of Fusarium wilt in watermelon (*Citrullus lanatus L.)* is accomplished by employing bio-functionalized manganese NPs. The suppression of pathogens were attributed to three main mechanisms: disruption of infection, enhancement of the host's defence response, and alteration of the microbial population in the soil (Noman et al. 2023). Thus, the Manganese NPs based nanofertilizers present a potentially practical approach for sustaining agricultural disease control and mitigation.

4.3 Copper Nanofertilizer

Copper nanoparticles stimulated photosynthetic activity and increased the rate by 35% in waterweed (*Elodea. densa planch*), even at low concentrations (Nekrasova et al. 2011). Metallic copper nanoparticles were mixed with soil and used for lettuce seedlings by Shah and Belozerova (2009). They observed an increased seedling growth of 40% in 130 mg kg^{-1} concentration and 91% in 600 mg kg^{-1}. Mixed soil with copper oxide nanoparticles was used for the plantation of *Spinacia oleracea*. Results revealed that adding copper nanoparticles improved physiological processes like photosynthesis in *Spinacia oleracea* (Wang et al. 2013). Dorjee et al. (2023) reported using copper NPs for managing fungal diseases in maize plants without affecting environmental health.

4.4 Iron Nano Fertilizers

An increase in germination percentage and yield was observed in *Pinacia oleracea*, *Cicer arietinum*, *Brassica juncea, Daucus carota* and *Sesamum indicum* when FeS_2 nanoparticles were applied to these plants (Das et al. 2016). According to the study of Disfani et al. 2017, increased plant growth and biomass accumulation were found in *Arachis hypogaea and Zea mays* after applying iron nanoparticles stabilized on the sand. Fe_2O_3 nanoparticles were added to the soil and used for peanut crops. Results showed an increase in the size of the peanut plants' roots and stems, their biomass, their height, and the amount of antioxidant enzymes and phytohormones compared to regular Fe_2O_3 particles (Rui et al. 2016).

4.5 Molybdenum Nano Fertilizers

Studies contributed by Ahmadreza et al. (2019) showed yield enhancement in the spinach crop after foliar application of Mo nanoparticles and reported a high nitrate assimilation rate. Nano fertilizer, Sodium Molybdate and Mo Chelate are separately applied as a foliar spray on cv. a strike under controlled environment green bean plants conditions along with soil application of ammonium nitrate as nitrogen source. Results revealed that the maximum biomass accumulation (24.31%) and yield (36.47%) were obtained in the foliar application of Nano Mo, as compared to the Chelate and Molybdate treatment (Muñoz-Márquez et al. 2022).

4.6 Nanofertilizer Products

Many researchers proved that the use of nonmaterial can increase yields and stress tolerance as compared to conventional fertilizers. By considering the requirement of nano fertilizers, some industries took part in developing such products. Though products are available, their cost is high and their requirement quantity is meager. The Nanofertilizer products is shown in Table 1 (Smeetraj et al. 2021; Prasad et al. 2017).

5 Advantages of Nanofertilizers

Nanofertilizers have advantages over conventional mineral fertilizers. Mineral nutrients can enhance sustainability of crop production and environmental friendliness if nano fertilizers are utilized to fertilize crops (Subramanian et al. 2015).

Several key benefits are:

1. In contrast to the quick and the crop, plants are fed by nano fertilizers, which slowly release nutrients from chemical fertilizers on their own in a controlled approach.
2. Nanofertilizers are superior to conventional fertilizers in nutrient uptake and utilization because they have much-reduced losses from leaching and volatilization.
3. Due to root exudates, molecular transporters, and an open passage from nanoscale pores, nanoparticles experience noticeably increased absorption. Moreover, different ion channels are used by a nanoparticle,

Table 1 Nanofertilizer products

Sr	Products	Specifications	Company Name	Country
1	Nano-Fertilizer Biozar	Organic materials, micronutrients and macromolecules combined	Fanavar Nano-Pazhoohesh Markazi Company,	Iran
2	Fulgro Nano Plant	Suitable for all living plant species, independent of the climatic or geological circumstances in India	Fulgro Nano Plant—Organic Liquid vermicompost Fertilizer	India
3	Geolife Nano Fertilizer Combi	Zn + Mn + Cu + Fe + Mg 16.6 + 3.8 + 3.8%	Geolife Nano Fertilizer Combi	India
4	Geolife NPK 19-19-19	Water Soluble Fertilize r, Nano fert NPK 19 19 19 fertilizers for plants	Geolife NPK	India
5	IFFCO	Nano Nitrogen, Nano Zinc, Nano Copper	IFFCO Nano Biotechnology Research Centre (NBRC)	India
6	Infinite Biotech	Bio-Nano Plant Growth Booster Promoter	Infinite Biotech	India
7	Nano Calcium (Magic Green) (1) kg	$CaCO_3$:77.9%, $MgCO_3$:7.4%, SiO_2: 7.47%, Na: 0.03%, K: 0.2%, P: 0.02%, Fe 7.4 mg L^{-1}, Sr: 804 mg L^{-1}, Al_2O_3: 6.3 mg L^{-1}, sulfate: 278 mg L^{-1}, Ba: 174 mg L^{-1}, Zn: 10 mg L^{-1}, Mn:172 mg L^{-1}	AC International Network Co., Ltd.,	Germany
8	Nano Capsule N	P_2O_5: 0.5%, K_2O: 0.7%, Ca: 23.9%, 0%; S: 0.8%; Mg: 0.2%, Fe: 2.0% Mn: 0.004%, Zn: 0.004%, Cu:0.007%;	The Best International Network Co., Ltd.,	Thailand
9	Green Nano	Corn, grain, soybeans, potatoes, coconut, and palm oil extracts	Nano Green Sciences, Inc.,	India
10	Fertilizer Nano Max NPK	Many organic acids are chelated with vitamins, probiotic JU, organic carbon, organic micronutrients/trace minerals, and important nutrients	Agri Sciences Pvt. Ltd., Janakpuri, New Delhi,	India
11	Nano Micro Nutrient (EcoStar) (500) g	Zn, 6%; B, 2%; Cu, 1%; Fe, 6% +; EDTA Mo, 0.05%; Mn, 5% +; AMINOS, 5%	Shan Maw Myae Trading Co., Ltd.,	India
12	Nano Plant Growth Promoter Magic Root 4the Generation	It increases the content of chlorophyll, protein, nucleic acid in the plant and thus accelerates photosynthesis	Magic Root 4the Generation	India
13	Nano Ultra Fertilizer (500) g	organic matter: 5.5%; Nitrogen: 10%; P_2O_5: 8%; K_2O: 14%; MgO: 3% P_2O_5: 9%; K_2O:14%;	SMTET Eco technologies Co., Ltd.,	Taiwan
14	P-Magic Gold 5gm Plant Growth Regulator (PGR)	Nano Technology Based Product (100% Organic) Decreases up to 50% cost of Fertilizers	P-Magic Gold	India
15	PPC Nano (120) mL	M protein, 19.6%; Na_2O, 0.3%; K_2O, 2.1%; $(NH_4)_2SO_4$, 1.7%; diluent, 76% WAI	International Development Co., Ltd.,	Malaysia
16	TAG NANO (NPK, PhoS, Zinc, Cal, etc.)	fertilizers chelated with minerals, vitamins, probiotics, seaweed extracts, and humic acid, as well as protein-lacto-gluconate	Tropical Agrosystem India (P) Ltd.,	India
17	Tropical nano PHOS	Nano phosphorus	Geetharam Agencies, Sole Proprietorship (Individual	India
18	TSR Organic fertilizers Flower Booster	Product of 100% Organic Nanotechnology	TSR Organic fertilizers	India

which increase ability of crop plants to absorb nutrients. Nanoparticles may cross material inside the plant, which results in efficient nutrient delivery to sink sites.

4. Nanofertilizers have far lower losses than synthetic fertilizers, which must be applied in more enormous quantities while considering the majority of their nutrients lost through emission and leaching.
5. The most significant advantage in terms of minimal losses that reduces the likelihood of environmental pollution is provided by nanofertilizers.
6. Nano fertilizers are superior to traditional synthetic fertilizers due to their relatively increased solubility and diffusion.
7. Due to a thin coating of nanoparticles encasing them, an intelligent nano fertilizer like fertilizers covered with polymers avoids inadvertent contact with soil and water and consequently minimizes nutrient loss. However, these are only accessible until plants are prepared to absorb the released nutrients (Iabal 2020).

6 Limitations: Phytotoxicity, Food Safety and Security Concerns

The utilization of nano fertilizers in sustainable agriculture encompasses a diverse array of applications; moreover, the realization of their full potential could be improved by limited constraints, primarily stemming from their phytotoxic properties (Anjum et al. 2015). The phytotoxicity of plants exhibits variability depending on the specific nanomaterials employed and their inherent characteristics. Nanoparticles are distinguished by their diminutive dimensions, typically measuring less than 100 nm. The unique characteristics and behaviours exhibited by nanoparticles at a small scale may give rise to ecological risks. As a result, various environmentally sustainable methods are being implemented to produce nanomaterials for various applications. The examination of the impact of nanoparticles on life forms and the environment, particularly soil, is a matter of considerable importance within the discipline of eco-toxicology (Anjum et al. 2015; Tripathi et al. 2017; Maghsoodi et al. 2019).

Significant concerns have been raised regarding the implications of nano fertilizers for the well-being and safety of individuals. A primary contributing factor to these concerns is the phenomenon of bioaccumulation of nanoparticles within successive ecological food chains. When nanomaterials are introduced into natural environments, they exhibit the capacity for prolonged persistence and can be taken up by various species and plants. Subsequently, these nanomaterials can traverse the physiological systems of these organisms, giving rise to notable adverse effects (Anjum et al. 2015; Tripathi et al. 2017; Maghsoodi et al. 2019). The accumulation of nanomaterials in different parts of plants induces the inhibition of cellular growth and, ultimately, cell apoptosis (cell death). Furthermore, this accumulation can harm soil microflora, impacting overall soil health (Mathur et al. 2022).

Therefore, it is essential to do comprehensive research on the detrimental impact of nano fertilizers on plants, soil health, food safety and security, and ecotoxicity to assess their practical viability. Nanomaterials that do not exhibit any substantial negative impact on plant health and the surrounding ecosystem possess considerable potential for practical application in improving agricultural productivity and quality. Moreover, advancing more sustainable techniques for synthesizing nanofertilizers can significantly enhance the environmentally conscious approach to biofertilizer production.

7 Conclusion

In this review, we have comprehensively explored current research on nanofertilizers in agriculture. The judicious application of nanofertilizers represents a promising avenue for maintaining an equilibrium between nutrient utilization and environmental sustainability. Diverse methodologies for nanofertilizer synthesis are available, with a notable emphasis on utilizing bioderived resources to mitigate production costs. Implementing straightforward application techniques minimizes soil fertilizer overload and concurrently reduces crop production expenses. Nano fertilizers can play a pivotal role in enhancing crop yield and quality, promoting sustainable agriculture and environmental well-being, provided they are made widely available, undergo formula standardization, and undergo thorough risk evaluation. Nevertheless, the realization of their full potential is hindered by a limited range of constraints, mostly stemming from the phytotoxic effect of some of the nanoparticles and their capacity to be assimilated into the subsequent trophic levels. Research in nanofertilizers should focus on minimizing environmental harm, optimizing nutrient efficiency, and enhancing crop productivity. A strategic contribution to sustainable farming practices can be made by progressively minimizing nutrient runoff and averting soil degradation. Precision in nutrient delivery may lead to reduced overall fertilizer usage, addressing concerns about resource depletion. Continuous research is key to unlocking the full benefits while ensuring environmental and human safety. The study reveals that the nano fertilizer has the ability to revolutionize agriculture by significantly enhancing crop yields, reducing environmental impact, and optimizing nutrient efficiency.

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Declarations

Competing Interest We want to confirm that the current publication is free of conflicts of interest.

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