Chapter 1
Maximizing Crop Yield with Macro and Micro Nano Enhanced Fertilizers

M. Reshma Anjum, J. Maheswari, K. Anusha, B. Sravya, G. Narasimha, and Kamel A. Abd-Elsalam

1 Introduction

The term "nanomaterials (NMs)" refers to materials having diameters ranging from 1 to 100 nm. Nanomaterials are special because of their small size and large surface area, which can have optical, physical, and biological effects. They are used in a variety of fields, including health, medicine, electronics, and agriculture, due to their special qualities (Rawtani et al., 2018; Seku et al., 2021). The process of engineering materials at the atomic level or at the molecular level is known as nanotechnology.

At present, conventional fertilizers, which are used in agriculture to increase crop yield, are widely being utilized across the world. The extensive use of commercial fertilizers, on the other hand, decreases the efficiency with which soil nutrients are utilized (Preetha & Balakrishnan, 2017). Excessive fertilizer use can cause heavy metals to enter the soil, plant system, and food chain, thus posing severe health concerns (Mahmoud et al., 2017). Nitrate contamination and eutrophication are caused by commercial fertilizer pollution in both subsurface and surface water systems. Toxic chemicals produced by fertilizer runoff eventually end up in aquatic bodies such as oceans, rivers, and ponds, causing considerable ecological damage.

M. Reshma Anjum · J. Maheswari · K. Anusha · B. Sravya
Department of Biotechnology, Sri Padmavati Mahila Visvavidyalayam (Women's University), Tirupati, Andhra Pradesh, India

G. Narasimha (✉)
Department of Virology, Sri Venkateswara University, Tirupati, Andhra Pradesh, India

K. A. Abd-Elsalam
Agricultural Research Center, Plant Pathology Research Institute, Giza, Egypt

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The use of traditional fertilizers generates large amounts of trash, which can cause a variety of health problems and have a detrimental effect on the economy (Khan et al., 2021). Discovering innovative and sophisticated methods is encouraged in order to overcome the excessive use of fertilizers without compromising yield. Nanotechnology, namely, the use of nanofertilizers (NFs), is one of the viable answers. Due to high surface area to volume ratio of nanoparticles (NPs), they are smaller in size and more reactive than are bulk materials and are believed to have the potential to transform agricultural systems (Singh, 2012). In agriculture, nanoparticles aim to reduce the number of pesticides distributed, reduce nutrient losses in fertilization, and enhance output through insect and nutrient control. NPs have several potential advantages, including improved food quality and safety, reduced agricultural inputs, and soil enrichment of absorbing nanoscale nutrients, among others (Prasad et al., 2017).

Nanotechnology, in fact, has the potential to enhance the whole existing agricultural and food sector by inventing new tools for plant disease treatment (Sharon et al., 2010), pathogen detection (Zuo et al., 2013), and enhancing plant nutrient absorption (Subramanian et al., 2015). Furthermore, nanotechnology has attracted increased interest in the agricultural area, particularly in the development of novel nanofertilizers to improve the efficiency and bioavailability of these new fertilizers while reducing their loss to the environment (Salama et al., 2019). A nanofertilizer is a nano-sized fertilizer with nanoparticles and nutrient encapsulation that may systematically release micro- and macronutrients to particular plant locations. By absorption or adsorption in a matrix, the nanostructured components in nanofertilizers are frequently integrated with a carrier complex. Chitosan (CS), polyacrylic acid, clay, and zeolite have all been described as nanofertilizer carriers (Cairo et al., 2017). Nanomaterials interact with fertilizers due to their high reactivity, resulting in enhanced and effective nutrient uptake for plants (Prasad et al., 2017). When nanofertilizers are used correctly, they may feed plants slowly, thus increasing nitrogen use efficiency (NUE), preventing leaching, minimizing volatilization, and lowering the overall environmental hazards (Solanki et al., 2015). Because of their high specific surface area, small size, and increased reactivity, nanofertilizers promote nutrient bioavailability. Nutrients may be encapsulated using nanomaterials by three distinct methods (Iqbal, 2019): (1) nanomaterials are encapsulated within them, (2) nanomaterials are applied as a layer, and (3) nanoemulsions are used to deliver the product.

Nanofertilizers perform a critical function in improving the yield of a wide range of crops. The nutrient usage efficiency of conventional fertilizers hardly reaches 30–35%, 18–20%, and 35–40% for N, P, and K, respectively, which has been stable for decades. Nanofertilizers are known to deliver nutrients slowly and gradually over a period of more than 30 days, which may help improve nutrient usage efficiency while avoiding side effects (Subramanian et al., 2015). Because of their ability to increase yield, reduce pollution, improve soil fertility, deliver slowly over a long period of time, significantly reduce nutrient loss, and provide a favorable environment for microorganisms, nanofertilizers have gained more attention from soil scientists and environmentalists (Vitosh et al., 1994). Nanofertilizers might be used as a powder or a liquid with a particle size of fewer than 100 nm (Jampílek & Kráľová, 2015). Then, nanofertilizer efficacy is determined by three variables: internal factors, extrinsic factors, and administration method. The method of nanoformulation preparation, the particle size of the nanoformulation, and surface coating are all intrinsic variables. However, extrinsic factors such as soil depth, soil pH, soil texture, temperature, organic matter, and microbial activity may also affect the potential use of nanofertilizers (El-Ramady et al., 2018a, b). Moreover, the route of administration/mode of application through plant roots or leaves (foliar) also plays a significant role in the absorption, behavior, and bioavailability of nanofertilizers. Depending on the nutritional requirements of plants, nanofertilizers are classified into three categories: macro-nanofertilizers, micro-nanofertilizers, and nanoparticulate fertilizers (Chhipa & Joshi, 2016). The following are some of the common characteristics of nanofertilizers: (1) they supply the necessary nutrients for promoting plant development through foliar and soil applications, (2) they are eco-friendly and low-cost sources of plant nutrients, (3) they have high fertilization efficiency, (4) they complement mineral fertilizers, and (5) they safeguard the environment from pollution threats. Accordingly, these nanofertilizers enable us to eliminate drinking water pollution and eutrophication and, as such, may be viewed as emerging alternatives to synthetic fertilizers (Guru et al., 2015). This chapter's purpose is to provide a detailed review of the various ways in which nano-enhanced fertilizers might increase crop production in agricultural settings. The reader will walk away with a solid comprehension of the many types of syntheses, characterization, and nanofertilizers. Additionally, a discussion of the possible benefits of utilizing nano-enhanced fertilizers in agricultural settings is included.

2 Synthesis of Nanofertilizers

Nanofertilizers are developed to increase the use of nutrient efficiencies by taking advantage of the distinctive properties of nanoparticles. Nanofertilizers are synthesized by stimulating nutrients individually or in mixtures against adsorbents with nano-dimensions. NFs are obtained through different methods such as the top-down method, bottom-up method, and biological synthesis, as shown in Fig. 1.1.

The top-down method involves physical methods for the production process, initiated by breaking down larger elements to yield small nanometric-scale materials (i.e., nanoparticles) using machine-driven abrasion. Examples of the top-down method include ball/pearl milling, high-pressure homogenization, microfluidization, nanocochleates, enantiomorphs, and controlled flow activation technology (Prasad Yadav et al., 2012). The methods based on this notion have some drawbacks, for instance, larger amounts of impurities and low control of particle size and uniformity. The bottom-up method starts with one molecule and moves by associating other molecules in the solution to form NPs by using chemical reactions. Examples of the bottom-up method involve hydrosol methods, precipitation methods, and spray freezing into liquid or supercritical fluid technology and

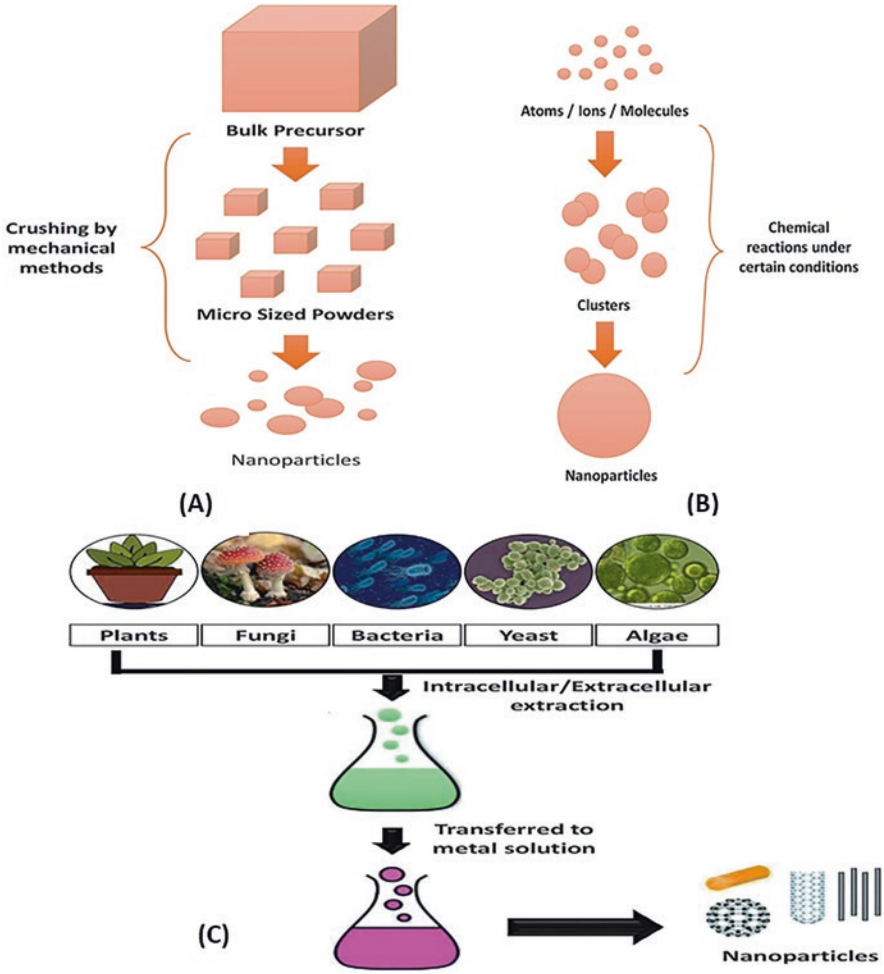

Fig. 1.1 (**a**) The top-down method; (**b**) bottom-up method; (**c**) biological method

self-assembly. Based on different varieties of nanomaterials, methods such as solvent diffusion, ionic gelation, complex coacervation, polyelectrolyte complex formation, solvent evaporation, coprecipitation, solid lipid NPs, self-assembly, and nanostructured lipid carrier suspensions are used (Abdel-Aziz & Rizwan, 2019). The bottom-up method is a chemically controlled synthetic process; as a result, it permits superior control of the nanostructure's size and reduction of scum (Singh & Rattanpal, 2014). Besides the top-down and bottom-up methods, there are many natural sources for the biological synthesis of NFs such as plants, bacteria, yeasts, and fungi. The major advantage of NFs synthesized through biological methods is the low cytotoxicity of the end product. Therefore, it is observed that there are many possibilities for the manufacturing of NFs and various advantages such as improved yield, a decrease in energy costs, and synthesis of materials with greater efficacy.

The incorporation of these physiognomies is likely to result in the production of agrochemicals that exhibit greater performance and supportable applications.

Metal oxides such as silver oxide (AgO), zinc oxide (ZnO), and magnesium oxide (MgO) are mostly used for the development of inorganic nanostructures. Organic compounds, carbon (C), polymers, and other compounds are mainly used as nanomaterials (da Silva Jr. et al., 2020). NFs can be synthesized based on the encapsulation technique. Encapsulation of fertilizers inside a nanoparticle is one of the novel amenities that can be performed in three ways: (a) by coating using a thin polymer film, (b) by encapsulating the nutrient within nanoporous materials, and (c) by delivering as particles or suspensions of nanoscale dimensions (Rai et al., 2012).

3 Characterization of Nanofertilizers

The shape, surface area, and surface chemistry of the produced nanofertilizers are all determined throughout the characterization process. Figure 1.2 shows the various characterization methods of nanoparticles, namely, X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM), and zeta potential (Shebl et al., 2019).

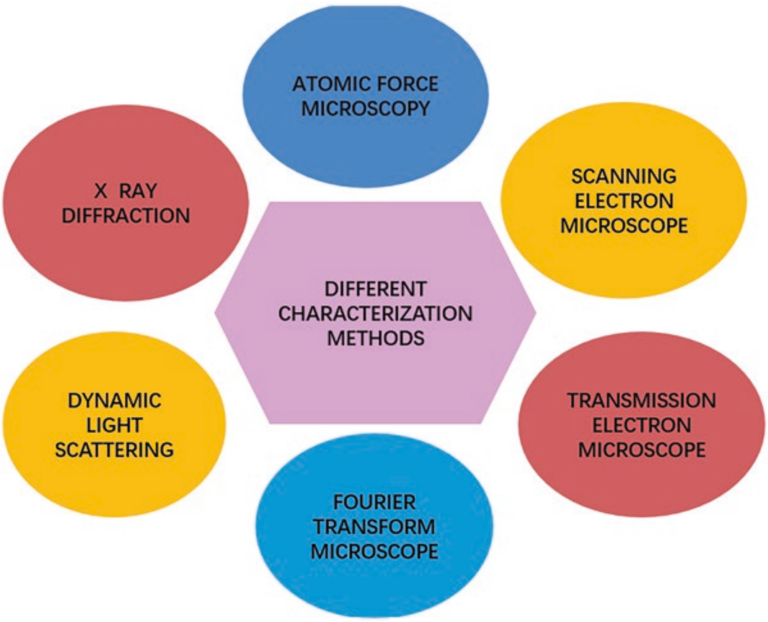

Fig. 1.2 Characterization methods of nanoparticles

3.1 X-Ray Crystallography

By penetrating X-rays deeply into the material, XRD is a widely utilized analytical method for observing the structural behavior and creation of synthetic nanocomposites. The diffraction pattern that results verifies the creation of crystalline nanoparticles. The Debye–Scherer equation is used to quantify particle size from XRD data by calculating the width of the Bragg reflection law according to the equation:

$$d = K\lambda / \beta \cos\theta,$$

where d is the particle size (in nanometers), K is the Scherrer constant, λ is the wavelength of the X-ray, β is the full width at half maximum, and θ is the diffraction angle that corresponds to the lattice plane (Prathna et al., 2011).

3.2 Fourier Transform Infrared Spectroscopy

In the wavelength range of 500–4000 cm^{-1}, Fourier transform infrared (FTIR) spectroscopy may be used to investigate the surface chemistry of synthesized nanocomposites with a resolution of 1 cm^{-1} (Rajeshkumar & Bharath, 2017). Infrared rays travel through the sample in FTIR spectroscopy; some are absorbed by the sample, whereas the rest pass through. The spectra that arise show the absorption and transmission properties of the sample material. To assess the function of biological molecules, FTIR spectroscopy is a cost-effective, suitable, easy, and noninvasive method (Rohman & Che Man, 2010).

3.3 Scanning Electron Microscopy

A scanning electron microscope is used to examine the topography and morphology of nanocomposites and to compute the size of different nanoparticles at the micro- and nanoscales. A high-energy electron beam is directed at the sample's surface using the microscope, and the backscattered electrons generate the sample's distinctive characteristics (Hudlikar et al., 2012).

3.4 Transmission Electron Microscopy

Transmission electron microscopy (TEM) is a highly helpful method for characterizing nanocomposites because it offers information on nanoparticle size and shape. Transmission electron microscopic pictures have a 1000-fold greater resolution than do SEM images and provide more precise information on the size, shape, and crystallography of nanoparticles (Almatroudi, 2020).

3.5 Zeta Potential

With particular operating parameters such as pH, temperature, and wavelength, the zeta potential is utilized to measure the particle size distribution of produced nanofertilizers (Patra & Baek, 2014).

3.6 Other Methods

A conductivity meter is used to measure physical characteristics such as pH and total dissolved solids (TDSs). To better understand the weight loss and reaction type of the produced nanocomposite fertilizer, thermo gravimetry/differential thermal analysis, (TG/DTA) studies are performed.

4 Types of Nanofertilizers

Nanoparticulate transporters assist in increasing agricultural output by modifying the role of fertilizers. Different kinds of NPs can be used as fertilizers or fertilizer delivery vehicles. Nanofertilizers are classified into three categories based on the type of nutrition they contain: macronutrient-based, micronutrient-based, and nanobiofertilizer-based. Figure 1.3 shows the types of nanomaterials used for plants and their role in plant growth and development.

4.1 Macronutrient-Based Nanofertilizers

An adequate amount of macro- and micronutrients, such as carbon, oxygen, hydrogen, nitrogen, phosphorus, potassium, calcium, sulfur, and magnesium, is required for plant nutrition. The first three are structural components that are taken from the environment, whereas the latter six are soil-derived. Macronutrients are classified into two categories: primary/main and secondary. Although the main macronutrients (N, P, K) are ingested in greater quantities, secondary macronutrients (Ca, Mg, and S), which comprise calcium, magnesium, and sulfur, are also essential for plant development.

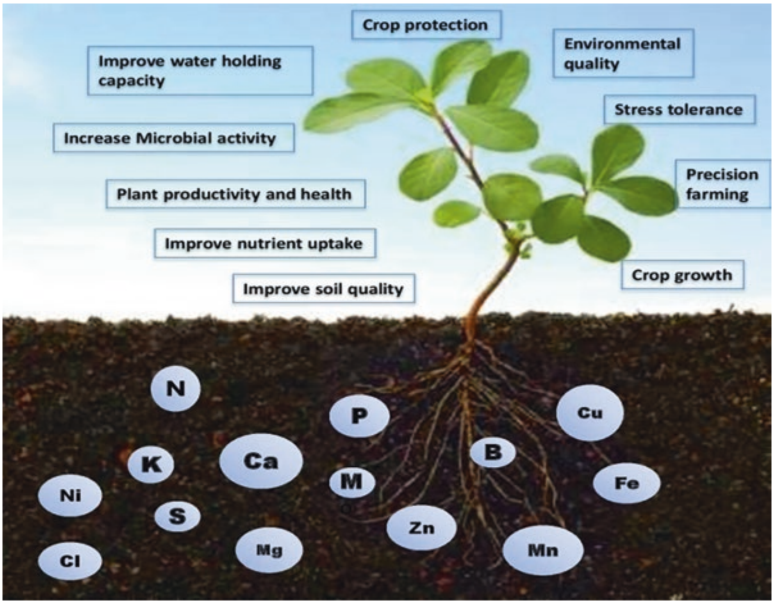

Fig. 1.3 Macro- and micro-nanominerals are available to plants, which results in various beneficial effects in the overall plant growth and development

4.1.1 Nitrogen Nanofertilizers

Nitrogen is the most important mineral ingredient for plants, and it is found in a variety of amino acids, proteins, DNA (deoxyribonucleic acid), ATP (adenine triphosphate), chlorophylls, and cell structure units. N is required for the majority of metabolic activities and regulatory pathways in plants (Preetha & Balakrishnan, 2017). Organic nitrogen molecules, ammonium (NH_4^+) ions, and nitrate (NO_3^-) ions are the three types of nitrogen accessible to plants. The majority of nitrogen is not entirely accessible to plants. This is because negatively charged nitrate has a lower affinity toward soil particle surfaces than does positively charged nitrate and, so, does not get readily absorbed by the soil. Because excess nitrogen is lost through denitrification, volatilization, and leaching during and shortly after field application, the widespread use of traditional nitrogenous fertilizers, such as urea, has generated many environmental problems. In comparison to the optimum ratio of 4:2:1, the present NPK ratio is 8.2:3.2:1, resulting in groundwater contamination and eutrophication in aquatic systems. As a result, there is a requirement for delivery systems that can release fertilizers at a slow pace in order to produce a sustained release of nitrogen during the crop season.

Various research studies have shown that nitrogen-based fertilizers, as opposed to conventional mineral urea, have a greater potential to improve output while reducing the drawbacks of conventional fertilizers. Nanocarriers like zeolites, chitosan, or clay can sync up with plant needs and deliver fertilizers at a steady rate, leading to better plant absorption and justifiable use of nitrogen. Nanozeolites and their mixes are widely used in the design of nanofertilizers due to features such as high surface area and the ability to synchronize nitrogen release (Preetha & Balakrishnan, 2017). According to certain reports, zeolites have the ability to reduce ammonia volatilization by sequestering ammonium N at exchange sites. Ammonia volatilization was observed to have reduced by 50% when 6.25% zeolite was added to the mix. Another benefit is that zeolite-bound ammonium is a suitable slow-release nitrogen source for plants. The plant growth substance, unlike conventionally used fertilizers, substantially minimizes nutrient loss to groundwater and the environment (Lefcourt & Meisinger, 2001). To regulate the retention and release of NH_4^+, zeolites can be used as fertilizer additions to decrease N-urea losses. The addition of a zeolite to a nitrogen source has been shown in the literature to increase nitrogen usage efficiency (McGilloway et al., 2003). In comparison to conventional urea, some researchers created intercalated nitrogen nanofertilizer (zeo-urea) formulations and showed a consistent improvement in maize crop growth, yield, quality, and nutrient absorption (Manikandan & Subramanian, 2016). The use of N NFs on starflower (*Borago officinalis* L.) led to a substantial increase in plant growth and, as a result, increased essential oil yields (Mahmoodi, 2017). Similarly, urea-modified zeolites were found to improve soybean (*Glycine max* L.) seed production when compared to synthetic fertilizers (Liu & Lal, 2014). *Brassica napus* L. was effectively grown using an N NF made by depositing urea onto a nanofilm (DeRosa et al., 2010). Similarly, both nano-N and chelated nano-N were beneficial in boosting yield and lowering nitrate leaching in a potato crop (*Solanum tuberosum* L.) (Zareabyaneh & Bayatvarkeshi, 2015).

Another study (Rajonee et al., 2016) found that a zeolite-based nitrogen nanofertilizer not only increased N accumulation in plants but also improved pH, moisture, and N accessibility in the soil after treatment compared to a traditional fertilizer. Finally, NFs are highly suggested since they can produce a delayed release of nitrogen, minimize volatilization and leaching rates, increase nutrient absorption, and boost crop growth and production.

4.1.2 Phosphorus Nanofertilizers

Phosphorus (P) is the second most important nutrient for optimum plant growth after nitrogen (N), as it is a structural component of phosphoproteins, phospholipids, sugar phosphates, coenzymes, nucleic acids, and metabolic substrates in plants, and it plays an important role in processes like photosynthesis, respiration, and DNA biosynthesis (Soliman et al., 2016). Phosphorus is required for the development of reproductive structures in crops at an early stage. Root stimulation, enhanced stalk and stem strength, improved flower formation and seed production, more uniform and earlier crop maturity, greater legume N-fixing ability, and improved crop quality and resistance to plant diseases are some of the particular growth characteristics linked to phosphorus (Preetha & Balakrishnan, 2017). Several factors can restrict the availability of P to plants, even if the amount of P in soils is considerably higher than what is required for plant development (Sohrt et al., 2017). Its immobilization with clay particles in the soil, for example, or its complexes with iron (Fe), aluminum hydroxides, and calcium in the soil limit its availability (Bindraban et al., 2020). Plants only absorb 10–20% of the given P fertilizers.

The increased usage of N fertilizers has exacerbated the problem by altering P microbial biomass and its ratios to N and C microbial biomass (Fan et al., 2017). To address these issues, a group of researchers developed and tested a nanotechnology-based method for phosphorus fertilizers. They showed that NFs can gradually deliver P for up to 40–50 days after application, whereas conventional phosphorus synthetic fertilizers deliver all nutrients within 8–10 days. As a result, it has been suggested that using NFs or slow-release materials like zeolites could increase the NUE of P for a variety of field crops (Bansiwal et al., 2006). In addition to contributing to a high NUE, a biosafety nanofertilizer, a source of P, was shown to considerably enhance fresh and dry biomass, increase fruit production, and improve quality by several times (Patra et al., 2013). Nanohydroxyapatite-based fertilizer increased the growth rate and seed production of soybean plants by 32.6% and 20.4%, respectively, as compared to the conventional P fertilizer (Liu & Lal, 2014). On *Adansonia digitata*, the use of hydroxyapatite NPs as a fertilizer carrier was investigated, and it was shown that hydroxyapatite NPs resulted in improved plant growth metrics, chemical contents, and anticancer activity of leaves when compared to various sources of P nanofertilizers (Soliman et al., 2016). The phosphorous usage efficiency of surface-modified zeolites has also been found to be higher than the traditional system's 20% (Preetha & Balakrishnan, 2017). In conclusion, P applied in the form of NFs might be a good alternative, especially in smart agriculture, since it has a long-term slow-release substance, which can decrease P leaching into groundwater and improve crop production and quality.

4.1.3 Potassium Nanofertilizers

Potassium (K) is the third most essential macronutrient after nitrogen and phosphorus. Even though potassium is not found in any plant structures or compounds, it plays a vital regulatory role in plants. It is required for virtually all of a plant's physiochemical activities, including its growth and reproduction (Preetha & Balakrishnan, 2017). Photosynthesis, photosynthetic translocation, protein synthesis, blooming stimulation, cell tissue strengthening, management of ionic equilibrium, regulation of plant stomata and water consumption, activation of more than 60 plant enzymes, and many other activities all require potassium (Preetha & Balakrishnan, 2017). Potassium-deficient plants are more susceptible to droughts, excess water, and extreme heat and cold (Taha et al., 2020). Pests, illnesses, and nematode assaults are also less resistant to them. Because of its major impacts on quality variables such as size, shape, color, taste, shelf life, fiber quality, and other quality measures, potassium is also known as a quality nutrient (Preetha & Balakrishnan, 2017). However, a K fertilizer's maximum usage efficiency is generally between 30% and 50% (Battaglia et al., 2018), implying that up to 50–70% of an applied K fertilizer might be wasted, resulting in significant economic losses and negative impacts on soil health and water quality (Czymmek et al., 2020). Several researchers have created and synthesized potassium nanofertilizers, concluding that they work better than traditional fertilizers. Some natural zeolites have high levels of exchangeable K^+, which can help plants develop faster in a potting medium. Data on the delayed-release impact of K from K-zeolites are available in Hershey et al. (1980). Because of their ion exchangeability with the chosen nutrient cations, zeolites can become an ideal plant development medium for delivering additional essential nutrient cations and anions to plant roots (Zhou & Huang, 2007). With a rise in equilibrium K concentration, the potassium sorbed on zeolites increases (Rezaei & Movahedi Naeini, 2009). A nano-potassium fertilizer formulation with a delayed K release rate was investigated and produced by certain researchers. The authors concluded that using a nano-potassium fertilizer might minimize K losses in the soil while also ensuring a longer-term supply of K to crops (Kubavat et al., 2020). In hot pepper (*Capsicum annum* L.), K-loaded zeolites enhanced the yield, harvest index, K concentration, and chlorophyll content (Jun-Xi Li et al., 2010). Due to enhanced nitrogen absorption, the assessed nano-K fertilizer for foliar application on *Cucurbita pepo* produced more leaves, higher product quality, disease and insect resistance, and drought tolerance (Fatemehsafavi, 2016). Lithovit, a nanofertilizer, has been shown to boost plant growth and production by increasing natural photosynthesis by providing carbon dioxide (CO_2) at the right concentration (Attia et al., 2016). It has been discovered that plants treated with nanofertilizers have greater K content than plants treated with conventional fertilizers (Rajonee et al., 2017). The root elongation rate was decreased in a dose-dependent manner when chitosan and methacrylic acid NPs were employed to encapsulate N, P, and K for assessment on garden peas. Despite the fact that lower doses resulted in the overexpression of several key proteins, all concentrations had genotoxic effects (Khalifa & Hasaneen, 2018). In comparison to other treatments, potassium nanofertilizer application at 150 + 150 ppm resulted in a substantial increase in nutritional content in peanut plant shoots and seeds (Afify et al., 2019). As a result, by decreasing K losses in the soil, K NFs can maintain soil health and enhance water quality.

4.1.4 Calcium Nanofertilizers

Calcium is important for mineral retention and movement in the soil as well as for neutralizing harmful chemicals, cell wall stability, and seed development. Although foliar calcium treatment has the ability to raise calcium concentration in fruits, it still has limited effectiveness in some cases, which can be attributed to calcium absorption limitations such as epidermal features, fruit penetration, cuticle structure and presence, and poor phloem Ca translocation rates (Wojcik, 2001; Danner et al., 2015). The impact of spraying calcium nanofertilizer and calcium chloride on the quantitative and qualitative parameters of preharvest apple fruits was demonstrated and the result showed that both fruit quality and quantity were considerably enhanced by nanocalcium treatment, with a maximum concentration of 2%

(Ranjbar et al., 2019). The impact of foliar application of nano-$CaCO_3$ on lisianthus development and blooming has also been studied. Spraying nanofertilizer at a concentration of 500 mg/L resulted in flowering 15 days earlier than for control plants, with a 56.3% increase in the number of flowers (Seydmohammadi et al., 2019).

4.1.5 Magnesium Nanofertilizers

Magnesium is essential for plant development because it makes up the core of the chlorophyll molecule, making it essential for photosynthesis. Mg is commonly lost from soil due to mobilization, leaching, and incorrect fertilizer application. The presence of other cations such as NH_4, Ca, and K affects magnesium absorption. The combination of magnesium and iron nanoparticulate solutions for foliar treatment in black-eyed peas improved virtually all of the studied characteristics (Delfani et al., 2014). Magnesium hydroxide NPs have also been investigated for their efficiency in seed germination and plant growth enhancement in vitro and in vivo on *Zea mays*. At a concentration of 500 ppm, the particles were shown to have 100% seed germination and enhanced growth (Shinde et al., 2020).

4.1.6 Sulfur Nanofertilizers

Sulfur is a secondary macronutrient that aids in the synthesis of chlorophyll, enhances nitrogen efficiency, and aids in plant defenses. The most frequent sources of S are sulfate (SO_4^{2-}) and elemental sulfur (S_8). Sulfate salts are easily taken up by plants, but the low S content does not fulfill the crop's desire for a significant sulfur feed. Furthermore, difficulties with SO_4^{2-} leaking result in considerable losses and environmental concerns. Elemental sulfur (S_8) has considerably greater S concentrations, but plants can only absorb it after biological oxidation by soil microbes, which are greatly controlled by fertilizer particle size (Valle et al., 2019). As a result, particle size reduction may have a substantial impact on the oxidation rate. As a result, developing sulfur nanofertilizers may be a viable option. The impact of sulfur nanofertilizers on the development and nutrition of *Ocimum basilicum* in response to salt stress was investigated and shown to have no significant influence on the characteristics studied (Alipour, 2016). Green synthesis of sulfur NPs was accomplished using *Ocimum basilicum* leaf extract, which was applied to *Helianthus annuus* seeds at various doses (12.5, 25, 50, 100, and 200 M) and irrigated with 100 mM $MnSO_4$ for pot study. Sulfur NPs were shown to reduce Mn absorption, improve S metabolism, increase seedling water content, and abolish physiological drought, indicating that sulfur nanofertilizers might mitigate the negative effects of Mn stress (Ragab & Saad-Allah, 2020).

4.2 Micronutrient Nanofertilizers

Many micronutrients, including silica, zinc, copper, and iron, have been synthesized at the nanoscale and used in plant growth management. Micronutrients are essential minerals that are needed in smaller amounts than N, P, and K and yet are critical for plant metabolic activities. Boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), chloride (Cl), and nickel (Ni) are a few examples of micronutrients. Despite the fact that micronutrients are only required in trace amounts, they are critical for healthy plant growth, profitable crop production, and increasing plant tolerance to a variety of stresses, including high pH, low organic matter, salt stress, prolonged drought, high bicarbonate content in irrigation water, and imbalanced NPK fertilizer application. Low crop quality and yield, imperfect plant morphology (such as fewer small xylem vessels), pervasive infection of numerous diseases and pests, low stimulation of phytosiderophores, and lower fertilizer use efficiency are some of the negative impacts of micronutrient deficiency-induced stress in plants. The production of micronutrients by nanoscale structures may improve their absorption and bioavailability, aid in the proper distribution of such micronutrients, and reduce micronutrient adsorption and attachment to soil colloids.

4.2.1 Iron Nanofertilizers

Iron (Fe) is a necessary nutrient for chlorophyll synthesis, DNA synthesis, chloroplast structure, respiration, and other metabolic pathways. Although plants require a tiny amount of Fe for growth, its deficiency or excess has a negative impact on the physiological and metabolic functions of plants, thus lowering output (Palmqvist et al., 2017). Because iron makes up about 5% of the earth's crust, soil contains plenty of it. However, due to the presence of insoluble ferric complexes at neutral pH values, a significant proportion of iron is unavailable to plants.

The use of highly persistent and slow-release nanoformulations to make iron available to plants is a promising strategy. In a wide pH range, iron chelate nanofertilizers are highly stable and provide a delayed release of iron. Another advantage of iron-based nanofertilizers is that they are free of ethylene-based chemicals, which cause plants to age into senescence prematurely (Armin et al., 2014). When compared to the controls, foliar application of iron nanoparticles (500 mg/L) to black-eyed peas significantly increased the number of pods per plant by 47%, the weight of 1000 seeds by 7%, the Fe content in leaves by 34%, and the chlorophyll content by 10%. Fe NFs have been shown in many studies to promote the germination and growth of various crops when compared with controls and/or synthetic Fe sources (Srivastava et al., 2014). In field trials, FeNP-treated peanut (*Arachis hypogaea* L.) plants grew healthier roots than did nontreated plants (Rui et al., 2016). In comparison to the controls (ferrous sulfate; $FeSO_4$), FeNP administration (2–6 nm) resulted in longer radical elongation during germination and higher fresh biomass in green gram (*Vigna radiate* L.) (Raju et al., 2016). Fe NFs (Fe_2O_3) in various doses (0, 5, 10, 20, 30, and 40 mM) have been employed on rose periwinkle (*Catharanthus roseus*). It was discovered that Fe NFs improved various growth parameters as well as chlorophyll and protein content when compared to plants that did not receive Fe NFs. In another study, iron oxide NPs (Fe_2O_3 NPs) were applied to plants at various concentrations for 70 days, resulting in considerable increases in growth metrics, photosynthetic pigments, and total protein content, with the largest quantity at a concentration of 30 μM (Askary et al., 2016). The use of γ-Fe_2O_3 NPs (20–100 mg/L) raised the Cl concentration in watermelon and *Zea mays* (Hu et al., 2018). In soybean plants, lower concentrations (0–0.75 g/L) of ferrous oxide NPs were found to increase Cl content and lipid and protein levels, whereas higher doses (0.75–1.0 g/L) reduced these parameters (Sheykhbaglou et al., 2018). A study of the effects of nanoscale zero-valent iron (nZVI) on a terrestrial crop, *Medicago sativa* (Alfalfa), found that 20-day-old seedlings had higher chlorophyll content, although carbohydrate and lignin content fell marginally (Kim et al., 2019). Cornelian cherry fruit extract was used to make Fe_2O_3 NPs, which resulted in statistically significant root and shoot biomass stimulation (Rostamizadeh et al., 2020). To summarize, Fe NFs can be an excellent alternative supply, especially in soils with Fe deficit.

4.2.2 Copper Nanofertilizers

Copper is required for a variety of physiological processes, including mitochondrial respiration, cellular transportation, and cofactors of antioxidant enzymes such as superoxide dismutase and ascorbate oxidase, as well as for protein trafficking and plant hormone signaling. Copper fertilizers are mostly used in crop protection formulations since copper is essential for plant health and nourishment. Copper deficiency causes a variety of problems, including necrosis, stunted development, reduced seed, grain, and fruit output, and, eventually, low crop yield (Priyanka et al., 2019). Due to their large surface area, high solubility, and reactivity, soil application of copper NPs in the form of fertilizers provides a likely route of exposure to plants The use of a CuONP nanofertilizer in the field enhanced the germination and root development of soybeans and chickpeas (*Cicer arietinum* L.) in recent experiments (Adhikari et al., 2012). Similarly, the germination rates of 65%, 80%, and 80% for soybean seeds treated with Cu, Co, and Fe nanocrystalline powders (40–60 nm), respectively, were greater than the 55% germination rate in a control sample (zero NF) (Ngo et al., 2014). Furthermore, after the application of CuNPs at a dosage of 5 mg/L, flavonoid content, sulfur assimilation, and the production of proline and glutathione in *Arabidopsis thaliana* improved (Nair & Chung, 2014). Copper NPs (CuNPs) biosynthesized (using *Citrus medica* L. fruit) at dosages of up to 20 g/mL enhanced the mitotic index in *Allium* extract, actively dividing cells (Nagaonkar et al., 2015). CuNP treatment, on the other hand, inhibited the development of water lettuce (*Pistia stratiotes* L.) (Olkhovych et al., 2016) and reduced the hardness of cucumber fruits (Hong et al., 2016). CuNPs were used to improve stress tolerance in wheat, as evidenced by the increased levels of proteins involved in starch breakdown and glycolysis, superoxide dismutase activity, sugar content, and Cu content in CuNP-treated seeds (Yasmeen et al., 2017). When pigeon pea (*Cajanus cajan* L.) seedlings were treated with biogenic CuNPs of 20 nm size, there was a significant increase in root length, height, and fresh and dry weights (Shende et al., 2017). The yield, nutraceutical characteristics, total antioxidant capacity, and lycopene content of CuNPs encapsulated in chitosan/polyvinyl alcohol (CS/PVA) hydrogels were all enhanced (Hernández et al., 2017). CuNP treatment of tomato plants has been shown to increase the firmness of the fruits while also increasing vitamin C, lycopene content, antioxidant capacity, and superoxide dismutase and catalase activity (López-Vargas et al., 2018). Cu-chitosan NPs sprayed on the leaves of finger millet plants, either alone or in conjunction with seed coating, increased yield and growth profiles as well as defense enzymes, thus leading to the prevention of blast disease (Sathiyabama & Manikandan, 2018). In conclusion, Cu NFs can considerably and favorably improve biochemical and yield characteristics, although the rate of administration must be carefully monitored.

4.2.3 Zinc Nanofertilizers

Zinc plays an important role in plant growth because it is a structural component and cofactor for numerous proteins and enzymes, for instance, isomerases, dehydrogenases, aldolases, RNA and DNA polymerases, and transphosphorylases. It is also involved in the biosynthesis of carbohydrates, maintenance of membrane structure and potential, protein metabolism, and regulation of cell division and defends plants against environmental stress and pathogens (Schmidt & Szakal, 2007; Broadley et al., 2007). The major limitation of conventional fertilizers is that most of the additional Zn is fixed in the soil, but zinc-based NFs show great potential (Wang et al., 2016). Zinc oxide (ZnO) is a form of zinc NFs, which are often used in contemporary agriculture as they are cost-effective and more efficient than synthetic fertilizers. They increase the growth, yield, and quality of crops. Foliar spray, seed priming (Sharifi, 2016), and soil mixing are the methods used for the application of Zn NFs to plants. High doses of Zn can negatively affect the development of plant growth by making certain metabolic changes in plants. The gradual release of Zn is due to the limited solubility of minerals and the sequestration effect of exchange, which releases trace nutrients to zeolite exchange sites where they are more readily available for plant absorption. Zeolite in the soil helps release trace elements and their uptake by plants. The existence of zeolites in unbiased soil enhances the release of certain cationic micronutrients. Germination in ryegrass was improved due to the entry of ZnO NPs into the root tissue (Lin & Xing, 2008). Using pumpkin plants as model crops, an elegant experiment was carried out to visualize the carbon-coated nanotubes in plant cells. Based on the study, the nanotubes serve as a supervisory tool to improve the nutrient transport system for plants (González-Melendi et al., 2007). ZnO NPs rich in zinc increases the level of indole-3-acetic acid (IAA) in roots, which, consecutively, increases the growth rate of plants (Pandey et al., 2010). In pearl millets, crop yield was enhanced by ZnNPs synthesized by biological methods and are used as NFs. A high concentration (1000 mg/kg) of ZnO NPs applied to the soil inhibits plant growth, but, at a low concentration (≤100 mg/kg), Zn uptake is enhanced by the cucumber plant (Tarafdar et al., 2014). Lisianthus showed improved chlorophyll content in leaf and petal anthocyanin besides an increased number of flowers, lateral branches, and leaves by foliar application of ZnNPs. ZnO NPs improved the sprouting of tomato (*Lycopersicon esculentum*) and cabbage (*Brassica botrytis*) (Broos et al., 2007) and sugar and protein content as well as antioxidant activities (Singh et al., 2013). Likewise, ZnNP application can increase leaf area, shoot growth, protein content, dry weight, and final yield in pearl millet, sunflower, maize, rice, potato, and sugarcane (Moghaddasi et al., 2017). Studies have demonstrated that the use of nanofertilizers in a number of crops, including cereals, vegetables, and fruits, can boost the rates of seed germination, root growth, plant height, biomass output, and yield. In addition, the use of nanofertilizers can lessen the amount of fertilizers required, which, in turn, can lessen the negative effects that agriculture has on the environment. The use of nanofertilizers can also boost the crop's nutrient content, resulting in food that is healthier and more nutritious (Zhang et al., 2022). It has been demonstrated that increasing the amount of zinc oxide nanoparticles used as a fertilizer can enhance the amount of zinc found in wheat grains, which is critical for maintaining human health. In conclusion, NFs have been used to improve plant growth and seed germination due to their ability to transfer across seed teguments, where they can increase oxygen and water uptake as well as improve tolerance against stresses that affect initial plant growth. This has been done in order to take advantage of the fact that NFs have the potential to improve plant growth and seed germination (Fig. 1.4).

4.2.4 Manganese Nanofertilizers

Manganese (Mn) is a crucial micronutrient that is involved in several biochemical processes such as biosynthesis of fatty acids, proteins and ATP, N metabolism, and photosynthesis. Irrespective of this, Mn can be noxious to various plants depending on the chemical nature of the acidic soil. Mn supports plants in dealing with various kinds of stresses. In comparison with commercially available MnSO4, MnNPs have been confirmed to be a better source of Mn. Research has proven that there was a significant increase in the yield and growth of maize, wheat, soybean, common beans, and sugarcane on the application of Mn (Fageria, 2001). On treatment with MnNPs, the yield of eggplant (*Solanum melongena* L.) enhanced by 22% (Elmer & White, 2016) and there was a considerable increase in the root length of lettuce (*Lactuca sativa* L.) with respect to Mn ions as compared to controls (Liu et al., 2016). However, MnNPs do not show any effect on the root length of white mustard (*Sinapis alba*) (Landa et al., 2016), watermelon (*Citrullus lanatus*) yield, and seed germination of lettuce (Liu et al., 2016). The MnNPs at the physiological level increase the activity of the electron transport chain by binding with the chlorophyll-binding protein (CP43) of photosystem II. Accordingly, plants fertilized with Mn nanoparticles exhibit a positive shift in their photosynthesis and nitrogen

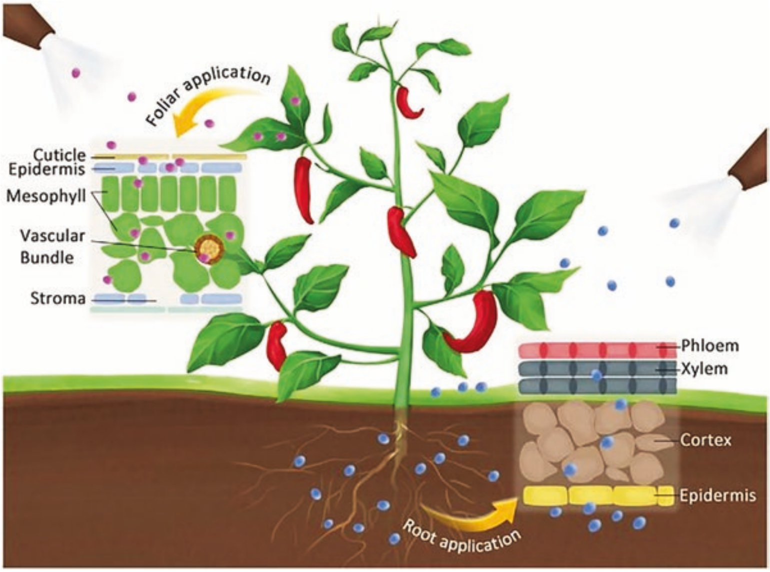

Fig. 1.4 The usage of nanofertilizers has been shown to promote the development of plants and germination of seeds. Nanofertilizers are a type of fertilizer that contains nanoparticles that have the potential to improve the availability of nutrients to plants and their ability to absorb those nutrients. Because of the high surface area to volume ratio of these nanoparticles, they are able to interact with plant roots and soil in a more productive manner, which ultimately results in increased nutrient uptake and utilization by plants. (Reprinted from Zhang et al., (2022). Under Creative Commons Attribution (CC BY) license (Wiley-VCH GmbH))

assimilation rates compared with their counterparts without Mn NPs. (Pradhan et al., 2013). MnNPs, as a nano-priming agent, help improve salinity stress in *Capsicum annuum*, which significantly improves root growth in salt-stressed and non-salt seedlings (Ye et al., 2020).

4.2.5 Boron Nanofertilizers

Boron (B) is an essential micronutrient required in lesser amounts by plants and plays a significant role in the formation of the cell wall, elongation of pollen grains and tubes, and transfer of photosynthetic products to the active areas of growth. It is also crucial for bark formation, transfer of certain hormones that affect stem and root growth, pollen germination, and flowering. For effective nitrogen fixation and nodule formation in legumes, an adequate amount of B is required. B deficit can be reduced by the use of conventional fertilizers, but the application of fertilizers frequently disrupts soil fertility and therefore results in environmental pollution. Nanotechnology has been considered as an alternate technique and is effectively used for the acquisition of B. Studies have proven that there is a significant increase in plant growth and yield by the usage of B NFs or NPs. B and its NPs sprayed at different concentrations exhibit greater results on increasing seed yield, the number of pods, and plant height at a concentration of 90 mg/L as compared with controls (B) (Ibrahim & Al Farttoosi, 2019). B NFs applied to an alfalfa (*Medicago sativa*) crop grown on calcareous soil reaped a maximum yield with appropriate forage quality (Taherian et al., 2019). Olive trees on treatment with nano-boron and nano-zinc at different concentrations produced a maximum quantity of fruits with high oil content (Genaidy et al., 2020). In conclusion, the application of B NFs can increase both crop yield and quality.

4.2.6 Molybdenum Nanofertilizers

Molybdenum (Mo) is essential in extremely minute quantities. The insufficiency of Mo is occasional; however, its insufficiency is usually found in *Euphorbia pulcherrima* (Thomas et al., 2017). Mo is a crucial component for the enzymes that change nitrate into nitrite and then ammonia before using it in the plant to synthesise amino acids. Besides, Mo is an essential constituent in the nitrogenase enzyme in nitrogen-fixing bacteria, which are crucial for leguminous plant crops. Likewise, Mo is used in plants for the conversion of organic forms from inorganic phosphorus. Efforts are made to study the properties of molybdenum NPs (MoNPs) as a fertilizer, due to the appealing aid of nanofertilizers. Application of MoNP solution, intact or in a mixture with microbes as a source of Mo, to chickpeas results in increased crop yield, disease resistance, and performance of legumes besides other crops (Taran et al., 2014). MoNPs synthesized using fungus such as *Aspergillus tubingensis* TFR29 at a standardized dose of 4 ppm show significant enhancement in root length, root space, root width, number of tips, beneficial enzymes, grain yield, and microbial activities in the rhizosphere (Thomas et al., 2017).

4.2.7 Silicon (Si) Nanofertilizers

Although silicon (Si) is not necessary for the completion of the plant biorhythm, it does offer some advantages to some plants in both normal and stressful situations. Because of this, it is divided into essential and optional micronutrients for plants. However, mono-silicic acid is the solitary form by which plants take up soil Si. Si plays an extensive role in improving resistance in plants against salinity, heat and water stresses, and heavy metal toxicity (Rastogi et al., 2019). The overall plant productivity can be improved by the application of silicon dioxide (SiO_2) along with organic fertilizers (Janmohammadi et al., 2016). In addition, the mesoporous structure of SiNPs makes them suitable nanocarriers for several molecules that are useful in agricultural systems. For instance, nanozeolites and nanosensors, which encompass the structure of SiNPs are effectively used in agriculture for improving the water-holding capacity of soil and monitoring soil dampness, respectively (Rastogi et al., 2019). Seedling vigor index (SVI) increased by up to 3.7-fold as compared with SiO_2 when seeds were primed with diverse concentrations (0.04–0.125 w/v) of a CS-Si nanofertilizer (Kumaraswamy et al., 2021). For emerging new varieties, which are resistant to several biotic and abiotic factors, SiNP-arbitrated targeting of biomolecules would be beneficial. These nanoparticles can offer eco-friendly and sustainable alternatives to numerous chemical fertilizers without damaging the environment. Si-NPs may therefore offer effective remedies for a variety of agricultural issues, including drought, pathogenicity, weeds, and crop production.

4.2.8 Nickel Nanofertilizers

Even though nickel (Ni) has been recognized as a trace mineral, its acceptance is highly significant for diverse enzymatic actions to maintain the cellular redox condition and some further activities responsible for physical, biochemical, and growth responses (Yusuf et al., 2010). NiNPs of 5 nm do not show any effect on the growth of wheat seedlings at low concentrations (0.01 and 0.1 mg/L), even though a slight upsurge was observed in the content of Chla and Chlb after subsequent application of NiNPs at 0.01 mg/L concentration (Zotikova et al., 2018).

4.3 Biofertilizer-Based Nanofertilizers (Nanobiofertilizers)

The term “nanobiofertilizer” refers to the purposeful coexistence of a biocompatible nanomaterial and a biological source-driven fertilizer, both of which have great efficacy. These features are designed to allow for slow and steady nutrient release over the course of a crop’s life cycle, resulting in improved nutrient utilization as well as increased crop output and productivity (Duhan et al., 2017). Probably, investigations over the last decade have revealed a progressive change in attention from chemical fertilizers to nano- and biofertilizers (Dhir, 2017). The use of nutrients in combination with biofertilizers at the nanoscale has been proposed as a cost-effective strategy for promoting proper nutrient control in smart agriculture (Kalia & Kaur, 2019). Biologically helpful microorganisms such as blue-green algae, mycorrhizae, bacteria such as *Rhizobium*, *Azospirillum*, and *Acetobacter*, and phosphate-solubilizing bacteria such as the *Pseudomonas* and *Bacillus* species make up a biofertilizer. These beneficial characteristics, although revolutionary and renewable, do not come without a price. Some of the technology’s limitations include vulnerability to nanoscale texture retention, poor on-field stability, varying activities under changing environmental conditions (pH sensitivity, temperature, and radiation exposure), a scarcity of useful bacterial strains, susceptibility to decomposition, and a disproportionately high dose necessity for a large area.

The nanoscale composition of a biofertilizer solves these problems by providing structural protection to biofertilizer nutrients and plant development factors, promoting microorganisms by nanoencapsulation-mediated nanoscale polymer coating

(Golbashy et al., 2016). In addition to boosting the benefits of biofertilizers, combining NFs with NMs and bioinoculants helps assure planned and targeted nutrient delivery to crops. According to research, NPs can influence the plant microbiome by improving nutrient availability or indirectly boosting the actions of plant growth-promoting *Rhizobacteria*. As a result, various NF application modalities are advised, such as applying NFs and biofertilizers independently or as nano-augmented biofertilizers (Gouda et al., 2018). The impacts of NMs are dose-dependent, meaning that larger concentrations have a negative impact on both flora and fauna. As a result, if they limit the growth of vegetation, their uses would be troublesome. As a result, appropriate and safer ways can improve the merits of using NPs at lower dosages that are less harmful to the environment. The nanoencapsulation method could be utilized as an effective alternative to extend the structural protection of a biofertilizer that has been delivered, improve its chemical shelf life, and disperse it in fertilizer formulations, enabling a sustained delivery. Aside from increasing nutrient release properties, the method also improves field performance and significantly lowers costs.

The nanobiofertilizer technique has several significant advantages, including enhanced inorganic nutrient use, greater crop product quality, and improved disease resistance. Through the nanoencapsulation phenomena, nanomaterials such as chitosan, zeolites, and polymers facilitate significant improvements in the uptake of organic nutrients, producing a continuous abundant quantity of nutrition for plants (Qureshi et al., 2018). A biofertilizer's extensive surface coating of NPs increases the dispersion of constituent nutrients. The constant release of biofertilizers from bound nanocarriers also provides long-term availability of the applied nutrients throughout the plant's life cycle (El-Ramady et al., 2018a, b). The organic content of nanobiofertilizers benefits in a synergistic way by enhancing soil nutritional quality through numerous processes. Despite providing necessary hormonal activities, some of these probable methods comprise atmospheric nitrogen fixation, siderophore creation, and phosphate solubilization through the activities of P-solubilizing bacterial and fungal strains (Mala et al., 2017).

By shortening the time it takes for wheat plants to reach physiological maturity, nanobiofertilizers improve spike length, spike quantity, grain production, and weight (Mardalipour et al., 2014). Treating *Brassica oleracea* plants using CS-urea NPs (1000 mg/L) and plant mycorrhiza reduced chemical nitrogen fertilizer input by 33.3%; this is similar to applying an entire dose of urea (Shams, 2019). The creation and execution of these compositions are hampered by a lack of basic knowledge about the interactions between NPs and plants. NFs have been shown to boost the harvest growth of plants and their components by lengthening the growing period (Mardalipour et al., 2014). In numerous investigations, the overall better response of nanobiofertilizer administration in agricultural plants has been documented, in terms of improved qualitative and quantitative crop growth metrics.

5 Nanotechnological Applications in Plant Promotions

The world's current task is to increase agricultural yields. There are several reasons why the yield will be insufficient when the world population hits nine billion people by 2050, as predicted. As a result, more acreage is required. It is anticipated that farming practices will lead to the depletion of the primary land. Other reasons might include shrinking land area, owing to urbanization, reduced nutrient availability in soil, falling soil organic materials, declining water resources and agricultural output, and the usage of synthetic fertilizers. Farmers' usage of synthetic fertilizers is hazardous to both individuals and the environment since large portions of these fertilizers remain in the soil. As a result, eco-friendly fertilizers must be used to replace conventional fertilizers. Nanoscience and technology play a significant role in resolving these issues. Many nanoparticles that have a wide range of uses in agriculture have been found. As a result, synthetic fertilizers are being phased out in favor of nanofertilizers, which are nontoxic to humans and the environment while simultaneously assisting in plant growth and development.

The discipline of nanotechnology has recently emerged as a potentially fruitful area for the development of novel approaches to bolstering the growth and health of plants. The creation of nanofertilizers is one way that nanotechnology is being put to use in the field of plant nutrition (Jiang et al., 2021). These are fertilizers that contain nanoparticles, which have the potential to boost the uptake and utilization of nutrients by plants, which, in turn, leads to increased plant growth and productivity. In addition, the use of nanofertilizers can lessen the amount of fertilizer that is required, which, in turn, can lessen the negative effects that agriculture has on the environment. It is anticipated that traditional fertilizers will be replaced by nanofertilizers by a factor of 50% in order to increase soil fertility. The creation of nanosensors that are able to monitor the state of a plant's health in real time as well as the conditions of its environment is another application of nanotechnology. As a result of their ability to detect shifts in humidity, temperature, light, and nutrient levels, nanosensors contribute significantly to the field of precision agriculture by giving farmers the ability to maximize crop development and output. The development of nanopesticides, which are pesticides that incorporate nanoparticles and may target specific pests without harming beneficial insects or the environment, is another use of nanotechnology that can be employed in the pest control industry. Nanopesticides can also minimize the amount of pesticide that is required, which, in turn, can lower the negative influence that agriculture has on the environment (Singh et al., 2013; Bhagavanth Reddy et al., 2022). In addition, nanotechnology can be utilized to construct nanocarriers, which are able to transfer nutrients, insecticides, and other bioactive compounds directly to plant cells. This enhances the effectiveness of these substances while simultaneously lowering the environmental impact they have (Fig. 1.5).

Nanomaterials as nanofertilizers have provided agriculture with a plethora of new opportunities. Nanofertilizers are the greatest choice for replacing macro- and micronutrients (Shukla et al., 2019). To increase soil fertility, nanofertilizers are

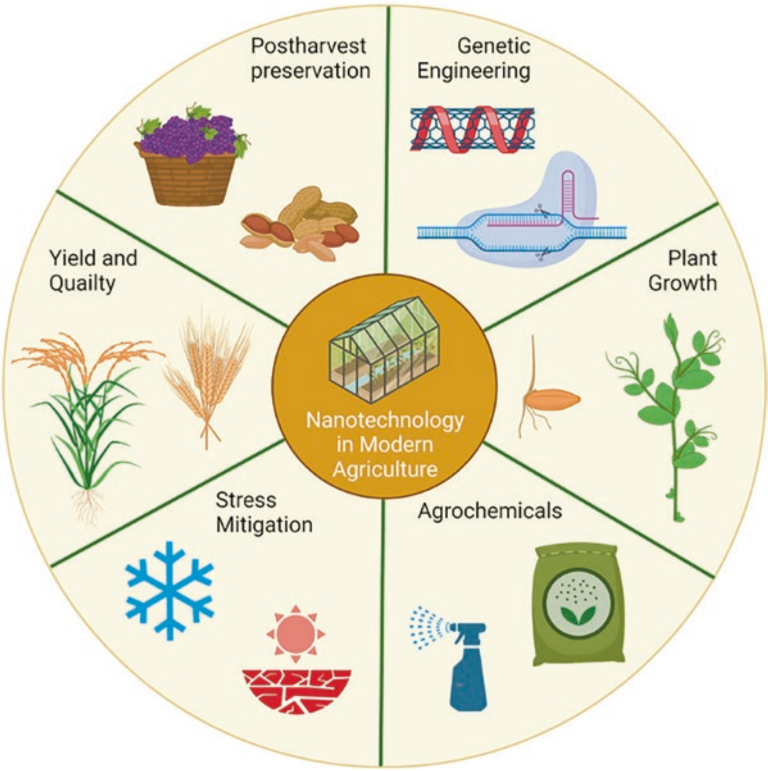

Fig. 1.5 The discipline of nanotechnology has recently emerged as a potentially fruitful area for the development of novel approaches to bolstering the growth and health of plants. The application of nanotechnology in plant promotion is a viable technique for generating environmentally friendly and sustainable solutions to boost plant growth and production while simultaneously lowering the negative impact that agriculture has on the surrounding environment. (Reprinted from Jiang et al. (2021). Under Creative Commons Attribution (CC BY) license (Springer *Nature*))

created by encapsulating plant nutrients into nanomaterials. Nanofertilizers come in a variety of shapes and sizes. They are (1) micronutrient nanoformulations, (2) macronutrient nanoformulations, and (3) nutrient-loaded nanomaterials (Kah et al., 2018). Control or delayed-release fertilizers, magnetic fertilizers, or nanocomposite fertilizers are all examples of integrated nanodevices that aid in the synthesis of micro- and macronutrients with desirable characteristics (Panpatte et al., 2016). Slow-release nanofertilizers have recently been utilized to reduce environmental contamination and the consumption of traditional fertilizers (Guo et al., 2005). Nanotechnological applications include agricultural chemical delivery systems, sensing systems to monitor environmental stress and crop status, and improving plant resistance to environmental issues and diseases. Some of the macro/micronutrient nanofertilizer applications are depicted in Table 1.1.

Table 1.1 A list of micro- and macronutrient nanoparticle types and their role as nanobiofertilizers

S. no.	Macro/micronutrient	Type	Role of NPs	References
1.	Nitrogen	Nanoparticle nanoformulation	Absorb soil nitrogen	Khan and Rizvi (2017)
2.	Phosphorous	Nanofertilizer	Improve water quality; lower eutrophication	
3.	Titanium	Nanoparticle	Increase light intensity absorption and photo-induced energy transfer	Sekhon (2014)
4.	Zinc	Nanoparticle	Enhance zinc availability to plant leaves	Khan and Rizvi (2017)
5.	Phosphorous	Nanofertilizer	Increase soybean seed quality yield	Sindhu et al. (2020)
6.	Intercalated nitrogen	Nanofertilizer	Yield, growth, quality, and nutrient absorption	
7.	Potassium	Nanoparticle	Increase leaf surface area, yield, and chlorophyll	Ardalani et al. (2014)
8.	Calcium	Nanofertilizer	Boost apple crop yields	Sindhu et al. (2020)
9.	Magnesium	Nanofertilizer	Improve seed germination	Sindhu et al. (2020)
10.	Sulfur	Nanoparticle	Sulfur metabolism, water content, manganese absorption	Ragab and Saad-Allah (2020)
11.	Iron	Nanoparticle	Seed weight, iron, and chlorophyll content	Sindhu et al. (2020)
12.	Zinc oxide	Nanoparticle	Increase leaf chlorophyll and petal anthocyanin content	Seydmohammadi et al. (2019)
13.	Copper	Nanoparticle	Enhance root length, height, and fresh and dry weights	Shende et al. (2017)
14.	Manganese	Nanoparticle	Extend root length	Sindhu et al. (2020)
15.	Boron	Nanoparticle	Boost plant height, pod quantity, seed production	
16.	Molybdenum	Nanoparticle	Increase yield, plant performance, and disease resistance	
17.	Engineered molybdenum	Nanoparticle	Enhance root area, root tip, root length, root diameter	

Nanobiofertilizers aid in the overall optimization of photosynthesis, nutrient absorption and translocation, and product and quality improvement (Sindhu et al., 2020). Nanopesticides, on the other hand, can effectively regulate delivery and make the medication effective even at low concentrations. According to research, nanopesticides are efficient in controlling bacteria, fungi, and insects. Many nanopesticides have been shown to have an effect on disease-causing insects. Because of their long-lasting release in soil, nanopesticides are more efficient in killing insects than are traditional pesticides, which wash away after rains (Khan & Rizvi, 2017). Nanoherbicide formulations are designed to eliminate herbicides' harmful features. They extend the shelf life of chemicals while also being plant-specific. They have their own means of preventing it from deteriorating as a result of environmental influences (Paramo et al., 2020).

The use of nanoparticles in the development of new products such as nanosensors play an important role in agriculture (Shang et al., 2019). For successful agricultural and environmental systems, nanosensors are utilized to monitor crop development, soil conditions, nutrient shortage, water scarcity, toxicity, plant diseases, plant health, product quality, and overall safety. Combining them with nanosensors results in nanobiosensors. These sensors are precise, quick, and sensitive. They contain a biological component that is linked to an active energy converter molecule. When there is an environmental shift, this aids in the detection of changes in the surrounding molecules (Ghasemnezhad et al., 2019). Bionic plants are those that have nanomaterials implanted into their cells and chloroplasts, allowing them to sense changes in both the environment and within the plant. These will play a bigger part in hybrid bionic plant research and development in the future.

Because the bulk synthesis of nanoparticles is simple, they can be produced in larger quantities. Nanoparticles have a huge influence on agriculture. They play an important role in the regulation and development of plant life. Plants that are treated with nanoparticles produce a higher yield. As a result, it is possible that the food crisis may be resolved in the near future.

6 Conclusions

The use of nanofertilizers has produced encouraging results in increasing crop output and enhancing plant growth. The following are some advantages of nanofertilizers for plant growth:

1. *Improved Nutrient Absorption*: Nanofertilizers can improve nutrient uptake effectiveness, allowing plants to absorb nutrients more efficiently from the soil. This may lead to enhanced plant growth and increased agricultural yield.
2. *Increased Nutrient Use Efficiency*: Nanofertilizers can make plants more effective at using nutrients, which results in a reduction in the amount of fertilizer needed to produce the same amount of growth as conventional fertilizers. Saving money and lessening the impact on the environment are the possible results.
3. *Improved Soil Health*: By improving microbial activity and encouraging the growth of advantageous microbes, nanofertilizers can improve soil health. Improved soil structure, nutrient availability, and water retention may result from this.

4. *Lessened Environmental Impact*: By requiring less fertilizers and lowering the likelihood of nutrient runoff and leaching, nanofertilizers can lessen the environmental impact of conventional fertilizers.
5. *Greater Resistance to Stress*: Plants that receive nanofertilizers can withstand environmental stresses like pests, salts, and droughts. This may lead to enhanced plant growth and increased agricultural yield.

In conclusion, nanofertilizers have demonstrated significant promise for enhancing crop productivity and encouraging plant growth. They can improve soil health, lessen their negative effects on the environment, raise stress resilience, and improve nutrient uptake and usage efficiency. It is crucial to remember that additional study is necessary to completely comprehend the long-term impacts of nanofertilizers on both plants and the environment. To reduce any potential dangers related to the usage of nanofertilizers, correct application methods and safety precautions should be followed.

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