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Efficacy of Nanofertilizers Over Chemical Fertilizers in Boosting Agronomic Production

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ABSTRACT

Global agricultural production cannot catch the increasing population's exigency. At different times, the world has faced food crises of varying intensity. Many steps have been taken after that to encounter the rising concerns. Nowadays, nanofertilizers are being experimented with as an alternative to conventional fertilizers. Nanofertilizers can be classified as macronutrients and micronutrients nanofertilizers. Synthesis of macronutrient nanofertilizers (nitrogen, phosphorus, potassium, calcium, magnesium, etc.) and micronutrient nanofertilizers (iron, boron, zinc, copper, silicon, etc.) can be done using chemical and green synthesis methods, which involves reducing agents, capping agents, dendrimers, microbial synthesis, solvents, and others. Composition of the nanofertilizers can be done using top-down and bottom-up approaches incorporating hydrocarbon polymer, dendrimers, microbes, etc., which decides their usage in various crops depending upon the requirement of the plant. Engineered nanofertilizers can improve crop yield by mitigating environmental pollution, environmental stress, and plant diseases. However, the unsystematic use of nanofertilizers can be a hurdle in its utilization. This article discusses various types of nanofertilizers with their unique properties and applications. Each category of nanofertilizers is explained considering their composition, particle size, concentrations applied, benefited plant species, and plant-growth enhancement aspects.

INTRODUCTION

The rapidly growing population has been causing food scarcity worldwide. Many factors, such as land degradation, climate change, and expanding population, threaten the food supply. The Food and Agriculture Organization (FAO) reported that about 670 million people in the world, constituting about 8 % of the world population, would be facing hunger in 2030, the same as in 2015 when the 2030 Agenda was launched (FAO et al. 2022). These statistics can increase to 840 million by 2030 if the present mode extends. As per the report, the factors responsible for worldwide famine are industrial decline and the uttermost meteorological phenomena. The UNO notified the need to improve global nutrition systems otherwise, zero hunger by 2030 cannot be achieved. The FAO's instructional global mapping facilitates readers to envisage hunger patterns.

In the present scenario, chemical fertilizers are becoming a threat in one way or another. Different factors are responsible for the same, but growing demand has resulted in excessive utilization of chemical fertilizers. These factors include limited cultivable lands, water scarcity, growing population, etc. (Shuqin & Fang 2018). Earlier, these factors oriented us toward the usage of chemical fertilizers. Although conventional supplements began to enhance crop growth and productivity, the intensive usage of these for a long time resulted in unimagined and devastating environmental impacts worldwide, such as groundwater contamination, water eutrophication, soil quality degradation, and air pollution.

Many approaches have been used to enhance fertilizer efficiency. Some of these involve the development of chemical fertilizers, changes in irrigation systems, crop hybrids, etc. Initially, when chemical fertilizers were used, an upsurge in production was noticed. However, in the long run, it resulted in various problems like soil pollution, water contamination, health issues, and many more. The application of nanotechnology for synthesizing fertilizers can be seen as a new step toward sustainable agriculture. It can be considered a promising option for dealing with the menace of food scarcity and bringing sustainability during climate change (Qureshi et al. 2018). Nanomaterials are particles whose size ranges between 1 and 100 nanometers (nm) (Hussain et al. 2016). Specified fertilization or localized supply can be done using nanofertilizers. Nanofertilizers can accelerate crop productivity by releasing the desired nutrient

(Al-Juthery et al. 2018a, 2018b). Applying the nanofertilizers correctly and systematically can bring requisite progress in crop productivity while keeping a check on the various environmental hazards caused by them. These benefits include fertilizer use efficiency, minimized volatilization, leaching, and lowering of environmental hazards.

Nanofertilizer can improve crop productivity by preventing various environmental problems and providing the nutrient at a site where it is required (Mehta & Bharat 2019). The technique of spraying liquid fertilizer is quite effective, whether micronutrients or macronutrients (Popko et al. 2018). Many agricultural specialists have been interested in generating and utilizing nanofertilizers (Khot et al. 2012). However, the highly specified research is inadequate. Besides, there is a perturbation that using nanofertilizers over the years might diminish soil fertility if nutrients are not used cautiously. Although, absolute soil analysis after crop harvesting can help overall soil fertility management and improve crop yield. The major objective of this review is to give an insight into various types of nanofertilizers to emphasize their efficiency in countering incoming challenges of food scarcity.

FERTILIZERS AND THEIR TYPES

Fertilizers are crucial for maintaining soil fertility and the productivity of crops in different environmental conditions. Rejuvenating the soil with fertilizers is indispensable to meet the deficiency of any nutrients in the soil. The dose of nutrients needs to be highly precise to ensure that neither the deficiency nor the accumulation of nutrients occurs in the soil. The deficiency of nutrients can hinder plant productivity, whereas the excess nutrients left in the soil may cause eutrophication or bioaccumulation into the aquatic environment (Subramanian et al. 2015). In this situation, nanofertilizers with high nutrient use efficiency can be exploited. Nanotechnology enables atom-by-atom manipulation such that precise and desired particles can be made compared to conventional methods. The most promising factor of nanofertilizers over chemical fertilizers is their excellent nutrient distribution (Liu & Lal 2015).

Chemical Fertilizers

Chemical fertilizers provide nutrients for plants' optimal growth. There are different types of fertilizers like nitrogen fertilizers (ammonium nitrate, calcium ammonium nitrate, ammonium sulfate, etc.), phosphate fertilizers (single superphosphate, monoammonium phosphate, diammonium phosphate, triple superphosphate, etc.), and potassium fertilizer (potassium chloride, potassium sulfate, potassium nitrate, etc.). Some other essential secondary plant nutrients include calcium, magnesium, and sulfur, which are not applied directly; instead, these are used in combination with primary nutrients (NPK), e.g., sulfur added to ammonium nitrate or urea or single superphosphate. Other micronutrient fertilizers comprises iron, manganese, boron, zinc, copper, etc.

Nanofertilizers

Particle dimensions and surface layering are significant factors that decide the effectiveness of nanoparticles and their usage. Characteristics such as organic matter content, soil fabrication,and soil pH also decide its usage (El-Ramady et al. 2018). There are different mechanisms for the absorption of nanofertilizers. Fig.1 represents efficient nutrient delivery systems and bio- interaction of nanofertilizers. These can be taken via plant roots or leaves in crops, so

(Source: Al-Mamun et al. 2021).

Fig. 1: Types of nanofertilizers and their smart nutrient delivery system in plants.

Table 1: Macronutrient nanofertilizers and their effect on different crops.

Macronutrients	Test plant/ soil type	Applied form of micronutrient	Output	Additional effect
Nitrogen (N)	Sugarcane	Urea and Nano- Nitrogen Chelate (NNC)	Improved sugarproduction (Alimohammadi et al. 2020)	Prevented leaching
Phosphorus (P)	In clay and loamy soil	Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$)	Doubled the efficiency of nutrient delivery from 23.44% (Calcium phosphorus) to 46.21% (Nanophosphorus fertilizers) (Tang & Fei 2021).	Hamper eutrophication
Potassium (K)	Peanut	Potassium nanofertilizers	Highly significant increase in plantparameters, with thehighest increase in the chlorophyll content (Afify et al. 2019).	Overall biomass increased
Magnesium(Mg)	Green gram , Groundnut	Magnesium oxide nanoparticles synthesized frombrown algae	Antioxidants are released to enhance chlorophyll production (Anand et al. 2020).	Stabilizes chloroplast (Cai et al. 2018)
Sulfur (S)	Groundnut	Sulfate-loaded surface-modifiednano-zeolite	Improved productivity in terms of root, shoot, kernel, and shell growth (Thirunavukkarasu et al. 2018).	Improved seed germination Seed germination

their absorption mechanism decides their bioavailability. Using these nanoparticles, two types of fertilizers can be made (i) nanoparticles that directly supply the nutrients (micronutrients or macronutrients) or (ii) nanoparticles that enhance the activity of the conventional fertilizer. The former is termed nanofertilizers, and the latter is called nanomaterial-enhanced fertilizers. Nanofertilizers can be categorized as macronutrient and micronutrient nanofertilizers.

Macronutrient Nanofertilizers

Macronutrients are responsible for the optimum growth of plants. These include nitrogen, phosphorus, potassium, calcium, sulfur, magnesium, carbon, oxygen, and hydrogen. Fig. 2 illustrates the availability of primary, secondary, and non-mineral nutrients to plants in their ionic forms. Nitrogen is the most important element for plant physiology. It forms chlorophyll molecules, imparting green color to plants which act as a site for photosynthesis. Deficiency of nitrogen results in chlorosis (yellowing of leaves) in plants. Nitrogen is a primary nutrient for plant growth, like potassium and phosphorus. An experiment was performed to determine the outcomes of Urea and Nano-Nitrogen Chelate (NNC) fertilizers on sugarcane production (Saccharum Officinarum) and nitrate drainage from the soil. It showed that the height of the sugarcane stems increased at the same rate in case of both fertilizers. However, the sugar content was found to be different. This study emphasized that nano nitrogen fertilizer (NNC) not only improved sugar production in sugarcane but also prevented nitrate leaching (Alimohammadi et al. 2020).

Potassium is a significant nutrient as it helps in the synthesize of biomolecules and activation of enzymes (Gosavi et al. 2017). Nano-potassium also enhances the absorption of other nutrients, such as nitrogen, calcium, magnesium, and phosphorus, along with root and shoot growth. However, it is usually more effective in the root region (Ajirloo et al. 2015). Highly enhanced chlorophyll content was observed when monopotassium was applied foliarly to peanuts (Afify et al. 2019). Saleem et al. (2021) coated diammonium phosphate(DAP) with nanoparticles (NPs) of potassium ferrite ($KFeO_2$ NPs). Calcium phosphate-derived phosphorus fertilizers rocks-based study emphasized that the solubility of hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) depends upon various factors such as pH ionic strength, Ca / P ratio, NPs size, etc. (Tang & Fei 2021). Its application almost doubled the nutrient delivery efficiency from 23.44% (Calcium phosphorus) to 46.21% (Nanophosphorus fertilizers).

Many studies have been conducted to evaluate the effect of magnesium nanofertilizers in crops such as legumes, horse grams, etc. Anand et al. (2020) studied magnesium oxide (MgO) nanoparticles to improve seed germination of mung beans (*Vigna radiata L.)*. For this, MgO nanoparticles were synthesized from marine brown alga, *Turbinaria ornata,* using the co-precipitation method. When mung bean seeds nano-primed with MgO (100 $mg.L^{-1}$) were used, it improved seed germination (%) compared to conventional hydropriming methods. MgO oxide nanoparticles were reported to have enhanced chlorophyll production by releasing free radicles. The antioxidant enzyme can counter the free radical to stabilize the chloroplast membrane (Cai etal. 2018).

Sulfur penetration via sulfate nanoparticles (Sulphate packed surface modified nano- zeolite), as well as ordinary sulfur, boosted the consumption of sulfur, thus improving the productivity in terms of the root, shoot, kernel, and shell growth in groundnut. Sulfur uptake was observed to be 0.76,

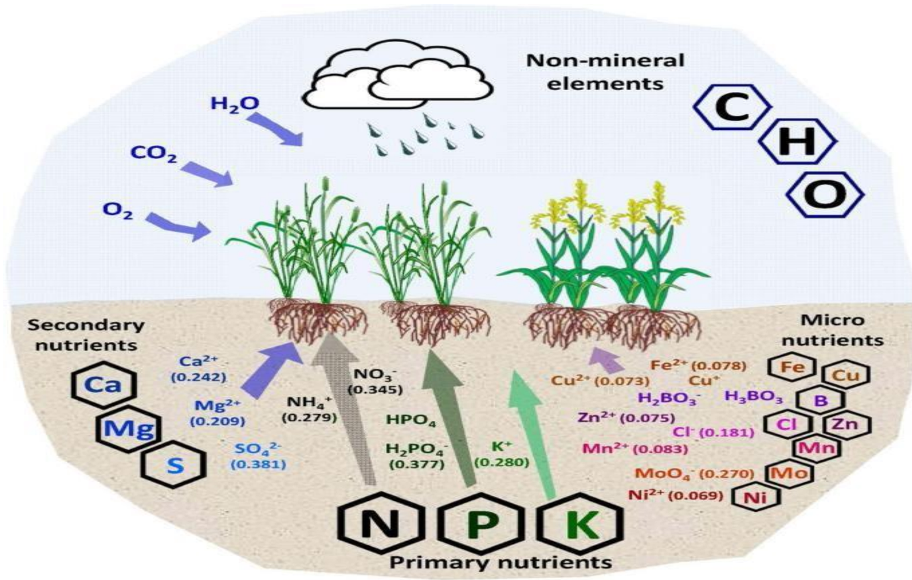

Fig. 2: Various types of nutrients available to plants. (Numbers in brackets refer to the hydrated radius (nm) of plant-available ionic species) (Bhardwaj et al. 2022).

40.5, 14.9, and 3.09 mg plant^{-1} when sulfur NFs were applied, whereas when conventional sulfur was applied, its uptake was found to be 0.43, 30.6, 8.37, and 2.15 mg plant^{-1} by the root, shoot, kernel, and shell, respectively (Thirunavukkarasu et al. 2018). When applied to a specific crop the various macronutrient application differs in terms of test plant or medium, applied concentration, and ionic form used. Table 1 represents the effect of macronutrients such as nitrogen, potassium, phosphorus, magnesium, and sulfur. Each nutrient has a distinct impact in terms of the growth of plants and other additional effects.

Micronutrients Nanofertilizers

Micronutrients are required in small qualities, but they can potentially disrupt plant physiology when deficient. These include iron, boron, chlorine, manganese, zinc, copper, etc. Table 2 illustrates the effect of different micronutrients on specific crops. Iron is considered a special nutrient for the plant as it promotes RNA synthesis, enzyme activity, photosynthesis, etc. (Mushtaq et al. 2020). Iron is a notably abundant element present on earth. However, its accessibility to plants is limited because of its dependency on soil pH (Alidoust & Isoda 2013). Iron deficiency can result in poor growth, lesser leaves, and lowered chlorophyll content. The distribution, accumulation, and metabolism of iron nanofertilizers have attracted various researcher's attention. However, the focus should be on maintaining an optimized concentration of nanofertilizers to avoid any toxicity to the plant and the surrounding.

The lowering of cadmium and lead accumulation in coriander plants was observed after using iron oxide (Fe3O4) nanofertilizer. It acted as a proliferator and antimicrobial agent (Fahad et al. 2014). Hasan (2015) compared the effect of chemical and biologically synthesized iron oxide NRs (Nanorods) on Zea mays' morphological and biochemical specification. It was noticed that biologically synthesized nanomaterials at low and medium concentrations showed optimum growth, whereas chemically synthesized nanomaterials reduced the growth when applied at a medium dose. As per the studies, the negative impact of a high concentration of NFs can be attributed to their accumulation around the root (Izadiyan et al. 2020).

Zinc is considered indispensable for development in humans, animals, and plants. It exhibits remarkable antimicrobial properties. Awan et al. (2021) synthesized zinc oxide nanofertilizer (ZnO-NFs) from zinc sulfate solution and seed extract of black seeds (*Nigella sativa* L.). It showed that ZnO-NPs application to the Broccoli resulted in increased seed germination, root length, shoot length, the weight of seedlings, leaf count, plant height, and leaf surface.

Boron (B), as a micronutrient promotes plant growth by developing cell walls, pollen grains, and tube elongation. It brings the translocation from leaves to the involved location, thus improving flower growth and fruit yield (Davarpanah et al. 2016). Ibrahim & Farttoosi (2019) studied the response of boron nanoparticles by spraying them on mung bean (*vigna radiata* L.). The finding of the study

Table 2: Micronutrient nanofertilizers and their effect on various crops.

Micronutrient	Test plant/Soil Type	Applied form of Micronutrient	Output	Additional effect
Iron (Fe)	Maize	Iron oxide nanorods	At low and medium concentrations showed optimum growth (Izadiyan et al. 2020).	Acted as a growth regulator and antimicrobial agent (Fahad et al. 2014).
Zinc (Zn)	Broccoli	Zinc oxide nanoparticles (ZnO-NPs) Using Zinc sulfate solution	Increased seed germination, root length, shoot length, the weight of seedlings, the count of leaves, plant height, and leaf surface (Awan et al. 2021).	Antimicrobial property
Boron (B)	Mung bean	Boron nanoparticles	Improved plant height, pods per plant, and total seed growth (Ibrahim & Farttoosi 2019).	N/A
Silicon (Si)	Maize	Chitosen-Silicon nanofertilizer	Improved plant growth and yield (Kumaraswamy et al. 2021)	Antioxidant- defense enzymes activities
Copper (Cu)	Maize	Copper oxide nanofertilizer	Positively regulates drought stress responses (Van Nguyen et al. 2022)	Disease management

suggested that the spraying stages of boron nanoparticles improved plant height, pods per plant, and total seed productivity.

Silicon (Si) is also a notable nutrient for plant growth. It is the most abundant element in the earth's crust after oxygen. In many studies, silicon nanostructures have also proven to be an excellent inhibitors of biotic and abiotic stresses. Chitosan-Silicon nanofertilizer showed a steady release of silicon to improve plant growth and productivity in maize crops. Its foliar sprinkling provides antioxidant-defense enzymes to equilibrate biological redox homeostasis by balancing O_2 and H_2O_2 content in leaves (Kumaraswamy et al. 2021). Tereshchenko et al. (2017) conducted a small plot experiment to study the impact of the solution of silicon dioxide nanoparticles on the monocotyledons and dicotyledons viz., hulless oat (*Avena sativa* l.) and lucerne (*Medicago sativa* L. Subsp. *varia* (Martyn) Arcang.). Various findings showed higher resistance in these plants.

Copper nanoparticles showed improved nutrient efficiency when compared to the bulk copper material. It is an essential micronutrient comprising many proteins and enzymes contributing to plant growth. Van Nguyen et al. (2022) emphasized that copper nanoparticle priming manages drought stress response in maize. Additionally, histochemical depicted that the accumulation of reactive oxygen species (ROS) in plants was lowered as a mark of intensification of ROS scavenging enzyme actions in aridity. Kasana et al. (2017) suggested that biosynthesized copper nanoparticles showed appreciable results against plant pathogens, but their application for boosting yield in the field needs thorough study.

SYNTHESIS AND CHARACTERIZATION OF NANOFERTILIZERS

Physical (top-down) and chemical (bottom-up) approaches synthesize nanofertilizers intended to provide plant nutrients. There are cationic nutrients ($NH4^{+}$, K^{+}, Ca^{2+}, Mg^{2+}) and anionic nutrients ($NO3^{-}$, $PO4^{2-}$, $SO4^{2-}$) to meet different nutrient deficiencies (Subramanian et al. 2015). The top-down approach is considered when a sizeable material is fragmented into nanosized entities. This process is complex, expensive, and requires high energy consumption. It operates in specific conditions of pressure and temperature. In the case of the bottom-up approach, nanostructures are synthesized by integrating the atomic or molecular species. This is based on wet chemical synthesis. Wet chemical processes had better nanostructure than the top-to-bottom approach. Various capping agents are used in colloidal synthesis, including heteroatom-operationalized long-chain hydrocarbons. One of them is oleic acid (OA), oleylamine (OAm), trioctylphosphine (TOP), dodecanethiol, etc., polymers that provide stability to nanoparticles (Kumar & Kumbhat 2016). Dendrimers macromolecules can also be used to develop and maintain nanoparticles as these are highly split (Duan et al. 2015). Yamamoto et al. (2019) synthesized quantum-sized titanium oxide nanoparticles using phenyl azomethine dendrimers (DPA) G4 as the capping template. Various attempts have been made for the green synthesis of nanoparticles following the fundamentals of green chemistry with a sustainable or green approach. It permits using water as the solvent in nanoparticle synthesis instead of relatively toxic solvents (Parveen et al. 2016). Biomolecules can be employed as capping agents for nanoparticle synthesis (Nasrollahzadeh et al. 2021). Biological methods include synthesizing nanofertilizers using proteins and/or peptides (Duan et al. 2015).

Characterization of nanofertilizers has become essential to evaluate the size and explore their properties so that these can be utilized as per the peculiarity. With the help of characterization techniques, safety issues regarding nanofertilizers can also be resolved before their application (Lin et al. 2014). Reduced silver nanoparticles in colloidal solution were observed by using a UV–vis spectrophotometer and absorption spectra of the supernatant (Elamawi et al. 2018)

Fourier transform infrared (FT-IR) spectroscopy characterized zeolite/Fe_2O_3 nanocomposites in which the FT-IR spectra were indicated within the range of 400–4000 cm^{-1} and 100–700 cm^{-1} (Jahangirian et al. 2020). Transmission Electron Microscopy and Scanning Electron Microscopy analysis depicted the surface characteristics and dimensions of the resultant NPs (Hodoroaba et al. 2014). A Field Emission Scanning Electron Microscope uses a zig-zag pattern instead of light. Shimadzu XRD- 600 with Cu Ka1 radiation (k = 0.15405 nm) was used to find out the crystal structure of the nanoparticles (XRD) (Deng et al. 2018).

Other techniques, such as Energy Dispersive Spectroscopy, Dynamic Light Scattering, Atomic Force Microscopy, Raman Spectroscopy, X-Ray Photoelectron Spectroscopy, etc., are also effective for characterizing nanofertilizers. Characterization is important as it helps in the controlled synthesis of nanofertilizers and their application for different crops. The development of faster, simpler, more efficient, and newer techniques for their characterization has now become an area of research. Different techniques can be integrated to understand these fertilizers and their characteristics in a better way.

UTILIZATION OF NANOFERTILIZERS

Applications of nanofertilizer in agriculture can bring sustainability by raising global food production since there is immense pressure on food production to fulfill the nutritional demand of the human population. Enriching the soil with more nutrients can counter the problem of low fertility (Cornelis et al. 2014). Various studies have analyzed the mode of interaction of nanofertilizers with different crops. Table 3 demonstrates the effect of a different supplied nutrient on various crops. These studies focus on the effect of different nanofertilizers in crops, viz. gain in fresh weight, increase in carotenoid concentration, improvement in leaf peroxidase activity over control or rise in density and fibrosity of plant parts, etc., which depicts the beneficial impact of nanofertilizers on plants.

Nanofertilizers for Boosting Growth and Yield of Crops

Various nanofertilizers have a definite impact on the development of plants. When nitrogen in its Chelated nanofertilizers form was applied to *Solanum tuberosum* (potato), improvement in their yield was observed (Al-Juthery & Al-Shami 2019). Potassium nanofertilizer with

Table 3: Major applications of different nutrients (micronutrients and macronutrients).

S.No.	Applications	Elements	Effect
1.	Enhance growth and yield of crop	Nitrogen, Potassium, Phosphorus, Silver, Zinc, and Iron.	NPK (nitrogen, phosphorous, potassium) nanofertilizers on *Coffea arabica* enhanced the chlorophyll amount and net photosynthesis rate (Ha et al. 2019). Silver nanoparticles accelerated seed growth rate in rice crops (*Oryza sativa)* by improving α-amylase function (Kumar & Nagesh 2019). Zinc oxide nanoparticles improved the sprouting of peanuts (*Arachis hypogaea*) (Seleiman et al. 2020). Iron nanoparticles significantly enhanced the root growth in peanut plants (Rui et al. 2016).
2.	Mitigate environmental stresses		
	(a) Abiotic stress	Nitric oxide	Antistressor (Nabi et al. 2019)
	(**b**) Biotic stress	Rhizobacteria (PGPR)	Antistressor (Khan et al. 2020)
		Nano silica	Effectiveness against insects, bringing a 100% mortality rate (El-Naggar et al. 2020).
		Silicon oxide, Zinc Oxide, Selenium, and graphene.	Elsheery et al. (2020) observed that SiO_2,ZnO, Se, and graphene nanoparticles lowered the unfavorable consequences of freezing injury in sugarcane by conserving the photochemical efficiency of photosystem II (PSII),photoxidizable photosystem I (PSI) andphotosynthetic gas exchange.
3.	To combat plant diseases	Copper, Titanium	Copper is very effective in lowering the symptoms of Turcicum leaf blight disease (Tamez et al. 2019). Fabricated TiO_2 also improved the yield and disease resistance in *Capsicum annuum* (Prakashraj et al. 2021).

foliar application showed an improved biomechanical and biochemical response in *Cucurbita pepo* (squash) (Gerdini 2016). Silver nanoparticles accelerated the seed growth rate in rice (*Oryza sativa)* by improving α-amylase activity (Kumar & Nagesh 2019). NPK (nitrogen, phosphorous, potassium) nanofertilizers on *Coffea arabica* (coffee plant) enhanced the chlorophyll content as well as the net photosynthesis rate (Ha et al. 2019).

Nanofertilizers for Mitigating Environmental Stress

Nanofertilizers can mitigate different environmental stress to improve crop productivity. In general, two types of stress are there, i.e., abiotic (50–70%) and biotic (40–60%) which results in the decline of crop productivity (Tiwari et al. 2022). Abiotic stress comprises heat stress, flooding, drought, and salinity, whereas biotic stress consists of bacteria, viruses, fungi, etc. Such stress can be controlled in plants by using various types of anti stressors viz. nitric oxide (Nabi et al. 2019), rhizobacteria (PGPR) (Khan et al. 2020), and strigolactones (Hussain et al. 2017). In maize plants, nanosilica increased the metabolic balance of chlorophyll, proteins, and cell wall transporters, thereby damping off stress-responsive enzyme activities. These also reflected effectiveness against insects by bringing a 100% mortality rate (El-Naggar et al. 2020).

Nanoparticles use can ameliorate the stress resistance in plants as it helps in alleviating reactive oxygen species (ROS) which are responsible for stress in crops. These PNCs (polyacrylic acid nanoceria) decline leaves ROS levels but improve the photosynthetic pace in *Arabidopsis thaliana* (Wu et al. 2017). When *Moringa* plants were sprayed with Hoagland (mixture of ZnO and Fe_3O_4) nanoparticles, a significant reduction in sodium and chloride concentration was observed. However, it enhanced nitrogen, potassium, phosphorus, magnesium, manganese, iron, and zinc content. (Amira et al. 2015). Zinc oxide nanoparticles improved the maturation of peanut seeds (*Arachis hypogaea*) (Seleiman et al. 2021). Iron nanoparticles significantly enhanced root growth in peanut plants (Rui et al. 2016). Some studies showed that nanoparticles stimulated proteobacteria while suppressing acid bacteria. Nitrogen and carbon cycles were affected by the nanofertilizers in a positive way (Kalwani et al. 2022). In addition, compounds secreted via root exudates and rhizospheric microorganisms combine with metallic species, influencing their assessment of plants and microorganisms (Faizan et al. 2021).

In drought-prone regions, plant water requirement is an ultimatum for subsequent decades. It was observed that utilization of the nano-fertilizers not only upgraded wheat grain yield by improving plant height, spike length, and the number of grains per spike but also mitigated the negative effects of water scarcity by enhancing the superoxide dismutase (SOD) activity (Ahmadian et al. 2021). Elsheery et al. (2020) observed that nanofertilizers (SiO_2, ZnO, Se, and graphene) reduced the harmful outcomes of freezing injury in sugarcane by conserving the photochemical effectiveness of photosystem II (PSII), photoxidizable photosystem I (PSI) and photosynthetic gas exchange. When iron nanoparticles were applied in water scarcity, it reduced the hydrogen peroxide levels, thereby lowering lipid peroxidation in *Brassica napus* (Rapeseed) (Palmqvist et al. 2017). Silicon-based nanofertilizers raised heavy metal resistance in rice (Wang et al. 2016).

Nanofertilizers for Disease Control in Plants

Copper nanoparticles showed improvement in plant growth and productivity. In addition,it was very effective in lowering the symptoms of Turcicum leaf blight disease (Tamez et al. 2019). Fabricated titanium oxide also improved the yield and disease resistance in *Capsicum annuum* (Prakashraj et al. 2021). Silver, Copper, and Zinc nanofertilizers regulate host defense by suppressing disease. They lower the active metals entering the environment when applied for disease management or antimicrobial activity (Elmer & White 2018). Antimicrobial functions of zinc NFs against bacteria have also been observed (Graham et al. 2016). Some intrinsic factors, such as particle size and surface coatings, and extrinsic factors, like soil texture or pH, decide these potentials (El-Ramady et al. 2018). Besides this, the application method significantly determined the utilization of nanofertilizers in crops (Prasad et al. 2017).

Nanofertilizers have great potential to enhance nutrient use efficiency. The nutrient delivery system of nanofertilizer is one of the significant reasons for orientation towards it (Liu & Lal 2015). This slow delivery system of nutrients because of the attachment of these with the nanoparticles (Solanki et al. 2015) provides nutrients for the long term. Moreover, nanofertilizers can be synthesized as per the crop's specified nutrient demand (Kah et al. 2018). Nutrient uptake of nano fertilizers is more compared to conventional fertilizers as it takes 40–50 days to slowly release nutrients using the former, whereas 4–10 days in the case of the latter (Solanki et al. 2015). In conventional nutrient management systems, there is more loss of nutrients due to leaching, making soil deficient of nutrients or accumulation around roots inhibiting growth and causing toxicity in the plant. In addition, using small quantities prevents soil from overloading with salts, as generally seen in the case of conventional fertilizer's over-application (León-Silva et al. 2018). A boost to nanofertilizer efficiency has been provided by fertilizer with the biosensor, which exhibits control over the delivery of the nutrients considering the soil nutrient level. Making the specific micronutrient available promotes plant growth (López-Valdez et al. 2018) which conventional fertilizer systems cannot achieve. Large surface area, reactivity, and nano size are the characteristics of nanofertilizers responsible for excellent diffusion of nutrients (Feregrino-Perez et al. 2018). Providing excellent nutrition nanofertilizers enhances plant's potential to combat biotic and abiotic stress.

LIMITATIONS OF NANOFERTILIZERS

The advantages of nanofertilizers are creating new ventures in the direction of sustainable agriculture. However, its drawbacks should also be examined before the market distribution (Zulfiqar et al. 2019). The large scale discharge of nanomaterials into the environment and the food chain is risky for human health (Gopalakrishnan Nair 2018). Nanofertilizers show excellent penetration power, which provides them with brilliant absorption efficiency. This factor can be harmful when nanofertilizers are in excess or when it gets to the wrong target. There are cases in which plants activate their defense system against NFs, especially in the case of metallic oxide-based nanofertilizers as in these parent nanomaterials, as well as the metal ions nanofertilizers, give aggravated impact (White & Gardea-Torresdey 2018). The excessive intake and assimilation in the plant parts can adversely affect human health. Transformation of nanoparticles is also a threat while applying them in the field, as these are highly reactive. When nanofertilizers are applied, being reactive, these tend to interact with the environment bringing change in their physicochemical properties. Nanofertilizer phytotoxicity can also exists as specific plants interact differently with these at particular doses (Ashkavand et al. 2018). As the nanofertilizers are highly reactive with their miniature size and small area (Konate et al. 2018), this raises a question about the suitability of their use by farm workers (Gopalakrishnan Nair 2018). There is a need to consider both the benefits and adverse effects before using these in the field. Risk assessment and hazard recognition of the nanofertilizers using their life cycle analysis are crucial, along with establishing advances for toxicological research (Ebbs et al. 2016).

CONCLUSION

The growing population and various other environmental issues have threatened food security. This makes it inevitable to look for some alternative approach to sustainable development. In this direction, efforts have been made from time to time. The most essential hindering factor regarding the usage of chemical fertilizers is their low nutrient efficiency which poses an obstacle in achieving sustainability of crop production. Moreover, as these are required in large quantities,it does not remain economically efficient. The high release rate of these chemical fertilizers does not correspond to their absorption by the plants, or the bioavailability of plants is relatively insignificant. Thus it brings the need to develop an alternative to chemical fertilizers that can cope with the challenges arising from their usage. Many studies have clearly emphasized that the nanofertilizers can increase a plant's productivity via various means, e.g., improved seed germination, photosynthesis improvement, increased nutrient metabolism and synthesis efficiency, and promoting the capacity to tolerate various kinds of stress bringing stability in growth. The potential of nanofertilizers as growth and yield enhancer in combating environmental stresses and pathogen resistance has been discussed in many studies. Another advantage is the smaller quantity applied, thus resolving the pollution problem and promoting the specified nutrient supply. However, the fact cannot be ignored that nanofertilizers usage needs to be highly systematic and supervised, prohibiting their free availability in the market and usage in the field. If judicious use of nanofertilizer is not done, phytotoxicity, high reactiveness, and biotransformation are the most prevalent phenomenon that can be seen. Hence, the focus of the concern should not be restricted to their benefits but also be extended to their negative aspects as well. Before its application, a proper risk assessment of the nanofertilizer life cycle is critical.

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