Chapter 4
The Potential of Nanocomposite Fertilizers for Sustainable Crop Production

Bhagwan Toksha, Shravanti Joshi, and Aniruddha Chatterjee

1 Introduction

A nanofertilizer is a product that serves the purpose of fertilizers at nano-scale. It is a product that transports nutrients to crops by modified means of transportation. The modified mean of transportation can be encapsulation, coating with thin layer or emulsion. Nanocomposite fertilizers are the formulations synthesized by combining two or more materials at nanoscale. The properites of starting materials gets curated as the composition of several nanomaterials gets captured within a material matrix. Nanocomposites evolve as an inorganic matrix hosting the organic phase, or vice versa, from an organic matrix hosting the inorganic phase. The design of Nanocomposite phase may aim at permeation of the desired component simultaneously preventing the other ill-favored components. Nanocomposites are heterogeneous or hybrid materials in a solid framework that can enhance the properties of the final product compared to those of conventional composites with individual phases. In this solid framework, at least one of the constituents has nanoscale dimensions (Neitzel et al., 2012; Sen, 2020). A variety of nanoparticles (NPs), including metals, metal oxides, zeolites, carbon-based materials, etc., are available. Nanocomposite fertilizers are used in almost every sector of agriculture. Various applications of nanocomposite materials influencing agricultural practices are depicted in Fig. 4.1.

B. Toksha (✉) · A. Chatterjee (✉)
Maharashtra Institute of Technology, Aurangabad, India
e-mail: bhagwan.toksha@mit.asia; aniruddhar.chatterjee@mit.asia

S. Joshi
Department of Plastics Engineering, Plastindia International University, Vapi, India

K. A. Abd-Elsalam, M. A. Alghuthaymi (eds.), *Nanofertilizers for Sustainable Agroecosystems*, Nanotechnology in the Life Sciences,
https://doi.org/10.1007/978-3-031-41329-2_4

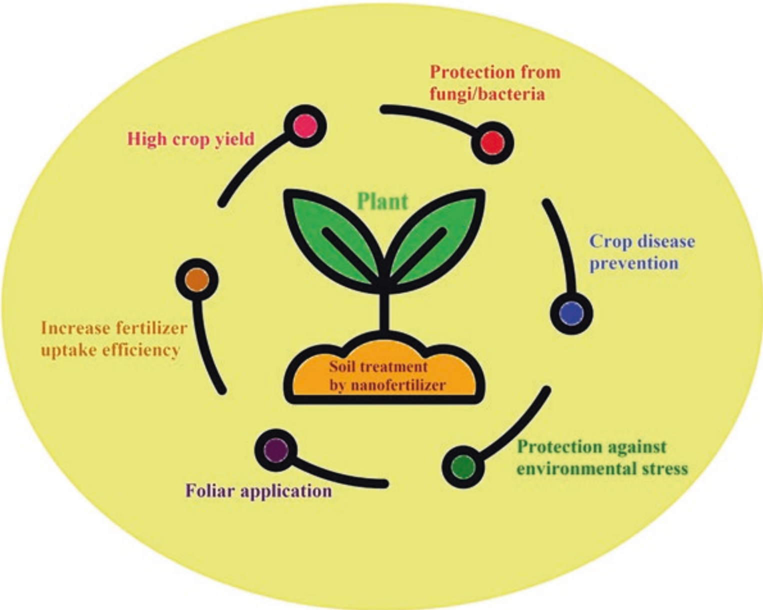

Fig. 4.1 Nanocomposite materials influencing agricultural practices

There is a lot to cover in the recent developments in nanotechnology for agriculture that have aimed to overcome the disadvantages of using conventional fertilizers. The role of nanocomposites in the fertilizer sector is particularly of interest here, as revealed by the expected increase in the use of nanofertilizers, which led to a compound annual growth rate (CAGR) exceeding 17% at a valuation of nearly USD 1.6 billion by 2030 (Jha et al., 2023). The characteristic advantages of nanotechnology, such as the extremely small size of nanoparticles, their extremely high surface area, and their high aspect ratio, provide potential solutions to address environmental concerns by replacing conventional fertilizers with nanocomposite fertilizers (Toksha et al., 2021). The various possible alterations to nanoparticle morphology, such as nanotubes, nanofilms, and nanoporous structures, enable the delivery of an optimal amount of the intended fertilizer via controlled or sustained release (Liang et al., 2022; Lohmousavi et al., 2020; Shaghaleh et al., 2022). Abiotic stresses, such as soil salinity, affect plant growth and crop production.

In India alone, salinity, alkalinity, and acidity are major factors that adversely affect food security (Kumar & Sharma, 2020). Salinity stresses roots and creates an ionic difference in the plant cell due to the buildup of Na^+ and Cl^-, which diminishes nutrient uptake thus inhibiting plant growth. This buildup of Na^+ and Cl^- in plant leaves reduces the photosynthetic area of leaves, affecting plant growth. Most crops commonly counter the harmful effects of salinity with the overproduction of a set of organic compounds. Such organic compounds act as osmolytes to counteract stress.

Additionally, crops also contain dynamic antioxidant enzymes, which are able to minimize the damage caused by environmental stressors. Such a natural defense, however, is inefficient in countering environmental stresses such as salinity. This situation demands taking economically viable and effective actions to minimize adverse effects and avoid the further increase in soil salinity. Soil salinity also changes plant physiology by disrupting its ionic balance and water homeostasis. It is also the root cause of damage in cellular-level redox homeostasis, which is caused by the escalated buildup of reactive oxygen. The losses due to saline soil have been estimated to cost over USD 27 billion dollars per year (Shahid et al., 2018).

The physiology of plants—i.e., the various functions of plant parts—enables photosynthesis and germination. Various phases of nanocomposites involving minerals and metal-based nanomaterials, such as oxides and ferrites, carbon matrices (e.g., graphene), carbon nanotubes, and biogenic materials, are synthesized for their possible applications in plant sciences. Table 4.1 presents the critical role and usage of nanocomposites in plant growth, plant physiology, crop quality, and sustainability on the basis of a few recent studies.

Their novel characteristics make nanocomposite products significantly different from their original forms of molecules and their bulk counterparts. Because of their unique properties, nanocomposites are garnering attention in research on agricultural processes, products, and applications. Nanocomposites include exciting alternatives to the existing synthetic chemical approaches to agricultural practices. These highly effective nanocomposites also modify application strategies, enable a slow-and-steady release, and improve target specificity. Nanocomposites endure over a prolonged period, which is also a vital characteristic for their applications in crop cultivation. This property influences their cost-effectiveness in that the desired activity can be achieved at a lower dose. Both lower-dose, target-oriented delivery and higher bioactivity will contribute to ecofriendly agricultural practices in the future. In-depth research in this area will ensure that the implementation of nanocomposite policies in crop sustainability and pest control will be useful and will help minimize environmental degradation and harm to humans. The aim of nanocomposites is to enhance the efficiency of the main matrix material by improving its physical, chemical, and biological properties. This ability to enhance physicochemical and biological properties also widens the application areas of newly produced nanocomposites in comparison with singly applied nanomaterials. Nanocomposites can be considered useful in the formation of nanocarriers, which are employed to carry and deliver the intended material by adopting both controlled- and slow-release modes. This improves the precision of farming practices such that it increases crop production and improves the nutrient values of consumable plant parts. Of course, this must be achieved without harming water and soil resources. The continuous reduction of dietary diversity and the increase in the consumption of staple crop-derived products have led to micronutrient deficiencies. Nanocomposites are expected to overcome such deficiencies by supplying micronutrients directly to plants. This problem of micronutrient deficiency is severe in areas where fertile soil lacks micronutrients.

Table 4.1 Applications of nanocomposite fertilizers in plant growth, plant physiology, crop quality, and sustainability

Aspect for improvement	Nanocomposite	Target	Mode of application	Critical role and usage	References
Plant growth	Bioinoculant + CeO_2	Fenugreek	Seed treatment	Increase in the uptake of essential micronutrients, improving to plant growth	Mary Isabella Sonali et al. (2022)
	Ag + graphene	*Stevia rebaudiana*	Green house foliar application	Increases in chlorophyll content, soluble sugars, and total phenol by 25–33% Higher flavonoids and total protein over 50%	Nokandeh et al. (2021)
Crop quantity and quality	Copper chlorophylline/ Silver and Copper chlorophylline /grapheme	Onion	Foliar application	Increased uptake of essential nutrient, improving crop quantity and quality	Merghany et al. (2019)
Crop quantity and quality	Ag + graphene	Melissa officinalis L	Foliar application	Higher plant productivity	Soraki et al. (2021)
Crop yield	Silica/Graphene + FeO + ZnO	Rice	Foliar application	Higher grain yield and increase in Zn and Fe uptake efficiency	Durgude et al. (2022)
Plant sustainability	GO-Ag	Wheat	In vitro— microdilution method In vivo—leaves	Crop disease prevention: antimicrobial agents against pathogenic fungi or bacteria	Chen et al. (2016)
	GO-CuO	Tomato, Pepper	In vitro and in planta	Reduction in *Fusarium* root rot and wilt diseases	El-Abeid et al. (2020)
	GO + chitosan/ethylene diamine tetra-acetic acid	Eggplant	In vivo—greenhouse	Improved plant immune response and nematocidal potential against *Meloidogyne incognita*	Attia et al. (2021)
	Mg + Chitosan	Rice	–	Antimicrobial activity against pathogens such as *Acidovorax oryzae* and *Rhizoctonia solani*	Ahmed et al. (2021)
	ZnO + $ZnFe_2O_4$	Guava	Through leaf extract	Improvement in plant immune response and prevention of transpiration, improving plant growth	Sahoo et al. (2021)

	$TiO_2/Cu_2(OH)_2CO$	Agar Medium	Agar medium under laboratory conditions	Antimicrobial activity against pathogenic fungal and bacterial infections	Liu et al. (2020)
	Montmorillonite + dimethyl silicone oil	Wheat	By spraying on leaf surface	Protection against powdery mildew infection in wheat crop via alleviation of physiological and biochemical stresses	Zhang et al. (2022a, b)
	Montmorillonite + peptide aptamer	*Stylosanthes*	By spraying on leaf surface	Protection against fungal anthracnose with improved antifungal activity through a secondary structure change Longer water retention achieved via hydrophobic interaction	Xu et al. (2022)
	Biopolymer arabinogalactan hosting Se NPs	Potato	Laboratory conditions	Antimicrobial activity against *Clavibacter michiganensis* ssp. sepedonicus	Perfileva et al. (2017)
	TiO_2 + N + and F	Tomato	Laboratory conditions	Antifungal activity against *Fusarium oxysporum*	El-Kahky et al. (2021)

NPs nanoparticles, *GO* graphene oxide

Recent studies have evaluated the role of nanoformulations in various aspects of plant growth and crop yield (Chakraborty et al., 2023; Jakhar et al., 2022; Sharma et al., 2022). A study aiming to determine the role of nanostructured materials in the variation of photosynthetic efficiency using a sustainable horticulture model was reported by Tighe-Neira et al. (2018). Other reports have shown that nanocomposites play roles in one of the growth phases of plants and in their variations, such as silica and its nanocomposites and copper and its nanocomposites. Also, Antul Kumar et al. and Matias Menossi et al. have elaborated on the inclusion of nanocomposites and bionanocomposites in sustainable agriculture.

The process that maintains the quality of crop yields is termed *biofortification* (Aziz et al., 2019; De Steur et al., 2017). There are a few well-known approaches to enhancing micronutrient content and bioavailability in edible staple crop tissues during plant growth (Carvalho & Vasconcelos, 2013). Using fertilizers; improving soil content so that all the required micronutrients reach the plant, known as agronomic biofortification; and practicing genetic engineering via plant breeding modification all improve the quality of crops (Dhaliwal et al., 2023). Using nanocomposite-based approaches for improving biofortified staple crop yields is a promising alternative to remediate micronutrient deficiencies (Achari et al., 2019). Food crops supplemented with micronutrients seem to have positive impacts on nutrition and human health (Dutta et al., 2022). A recent review has updated the approaches that use nanoparticles to overcome nutrient deficiencies. The fortification of micronutrients in plants will in turn fulfill humans' nutrient requirements (Kapoor et al., 2022).

The objective of this chapter is to present an up-to-date understanding of nanocomposite fertilizers. What has been recently carried out in the field of nanocomposite fertilizers and how these findings will be helpful in developing overall fertilizer policies, including those for nanocomposites, are summarized in this chapter. This chapter also aims to provide a readable synthesis of the recent standard resources of nanocomposite fertilizers available in the literature. Moreover, this chapter reviews and provides updates on the contemporary knowledge on and the future of nanocomposites for promoting sustainable crop cultivation under the dynamic global climate.

2 Nutritional Nanocomposites

The role of nanocomposites encompasses plant growth, plant physiology, crop quantity, and crop quality. Nanocomposite fertilizers are promising alternatives to their bulk and conventional counterparts thanks to their enormous potential. Various factors, such as the conditions in which the nanocomposites are applied, are considered and evaluated for each plant. As a result of efforts taken for sustainable agriculture, world cereal production is expected to increase by the end of the 2020s. The main crops that will benefit from this growth include maize, wheat, and supplementary coarse grains. Increased research on seed varieties and superior agricultural modifications have contributed the most to increasing crop yields. However, these attempts have fallen short in alleviating the impacts of climate change and production constraints. In the majority of developing countries, production constraints such as investment financing and land-tenure issues are quite serious. The price of fertilizer is a vital consideration in agricultural financial investments. The causes of the dynamic changes in cereal prices include seasonality, financial constraints such as transport costs (which depend on energy/oil prices), and agricultural commodity price volatility (Kwas et al., 2022).

A greener approach to increased agricultural productivity could lead to possible pathways to reduce the carbon emissions of agriculture and to increase the area for crop production. Of these pathways, the area for crop production is almost at its limit and arguably cannot be extended further. Increasing the food production index is necessary to increase cereal food production while reducing agricultural carbon emissions. Alternate designs include using ecofriendly, effective fertilizers that can enhance crop yield in healthy, ecological settings (Koondhar et al., 2021). Cereals and other food grains are important because of their nutritional contributions and low costs (Beyer, 2010). Understanding the natural functionalities and modifications of a given crop could be vital in designing nanocomposite fertilizers (do Nascimento et al., 2022). For example, alterations in the germination process lead to the increased bioavailability of nutrients such as carbohydrates and proteins (Poole et al., 2021). Another example of this kind is bioactive compounds' leading to increased levels of antioxidants and fiber (Erenstein et al., 2022). The nanocomposite fertilizers enriching crop products can reduce many severe medical conditions due to malnutrition by increasing the intake of bioactive food components, particularly dietary fiber. The hidden hunger problem, due to food containing low levels of mineral elements, could be solved by using nanocomposite fertilizers. While aiming to meet humans' nutritional requirements, ecological boundaries must not be crossed and resources must not be overexploited because those would further exacerbate environmental degradation and water scarcity. Climate changes and crises further compound problems such as crop adaptation and crop losses. The application of nanocomposite fertilizers has been adopted as a novel agricultural practice to overcome difficulties in maintaining worldwide cereal production, enhancing crops' crucial nutrients, and reducing the levels of poisonous elements in the edible parts of agricultural crops. However, these materials' deleterious effects on crops' physiologies, antipathogen activities, and action mechanisms remain challenges for the scientific community to overcome. Generating nanocomposite fertilizers via a green synthesis method would reduce the potential toxicity of the nanocomposite fertilizers in comparison with those obtained via conventional approaches that use environmentally degrading precursors (García-Ovando et al., 2022). The improvements in nutrient availability thanks to nanocomposite fertilizers, as compared to conventional fertilizers, is discussed in the following section. Its subsections are as follows:

2.1 Plant growth
2.2 Plant physiology
2.3 Crop quantity and quality

2.1 Plant Growth

More than 14 mineral elements—in the form of micro- and macronutrients, including oxygen, carbon dioxide, and water—are required for a plant to grow (Mengel et al., 2001; White & Brown, 2010). The physiological and biochemical processes of plants can be improved by using nanocomposite fertilizers to increase nutrient availability. This in turn contributes to the plant's overall growth. The dynamics of including nanophase materials for plant growth have been focal points of research over the past decade (Amer et al., 2021; Sigmon et al., 2021; Verma et al., 2018, 2019). Industrialization has long contaminated soil and water resources, and such contamination has spread all over the planet. The main concern here is that heavy metal stress conditions hamper the metabolic, physiological, and biochemical characteristics of plants and plant growth. Heavy metal stresses also affect other indications of plants' life spans, such as seed germination, photosynthetic activity, root length and size, root-tip mitosis, and micronucleus induction. Heavy metals accelerate aging and cause roots to be shorter, thinner, and less developed overall. Nanocomposites formed under gamma irradiation involving chitosan, Ag, and Mn-Mg ferrite improved plant growth in cabbage under Cd stress. The Cd content was reduced in leaves and roots, and the chlorophyll values increased. Including this nanocomposite also reportedly improved the antioxidant and nonantioxidant enzymes of the target plant (Abdel Maksoud et al., 2022). The environmental hazards of urea rise from urease hydrolyzation. Urea's leaching into the nearby environment reduces nutrient-uptake efficiency. A fertilizer synergist (FS) of sodium humate transported by a hydrogen-bond nano-network leading to high biosafety and a decrease in agricultural pollution was reported by Linglin Zhou et al. (2017). Images from field experiments on potato, corn, and rice crops are depicted in Fig. 4.2.

The term *micronutrients* in the context of agriculture refers to elements that are abundant in soil. Elements such as Cu, Fe, Mn, and Zn are subsumed under this class, and they are required in smaller amount but play critical roles in plant growth and development. Micronutrients enable healthy plant growth, whereas their deficiency causes abnormal growth in plants, and higher concentrations may hamper plant growth. One role of micronutrients in plant growth and development is to maximize crop yields (Chrysargyris et al., 2022; Tripathi et al., 2015). The routes that micronutrients take in plants, including soil broadcast spreaders and foliar sprays, suffer from conventional drawbacks such as volatilization, leaching, and surface runoff. In addition to this disbursement of micronutrients through the soil, seed treatment is useful for early critical plant growth and for crop yields. The fixation or unavailability of these nutrients is sensitive to many climatic and edaphic conditions.

Copper in trace amounts is one such micronutrient that is essential for plant growth. Besides exhibiting antibacterial, antifungal, and insecticidal activities at the nanosize, it also inhibits plant growth in higher concentrations (Jampílek & Kráľová, 2022). Chitosan/polyacrylic acid/copper nanocomposites obtained via

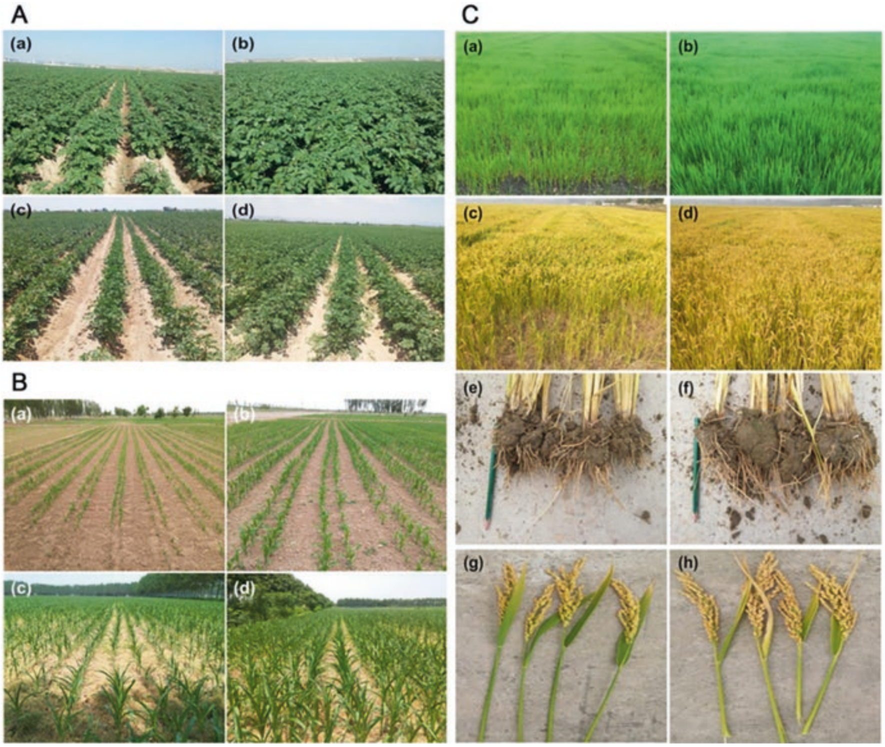

Fig. 4.2 Field photographs of (**a**) potato, (**b**) corn, and (**c**) rice at their seedling and mature stages, including rice roots and ears. (Reprinted with permission from Zhou et al., 2017)

copolymerization were provided through foliar method to onion plants (Abd El-Aziz et al., 2019). This experiment demonstrated the antibacterial activity of synthesized nanocomposites and resulted in the higher growth and yield of onion bulbs.

Zinc is a metal to which a large number of proteins are bound and is used in all six enzyme groups (Osman et al., 2021). Nanocomposites, such as zinc NCs, have proven to be beneficial to plants grown under salinity or drought stress (Batista et al., 2020). Improvement along various indicators—such as enhanced plant growth, chlorophyll content, and fewer aborted seeds per pod with better antioxidant enzyme activity—and the accumulation of osmolytes are attributed to the use of zinc NCs (Kheir et al., 2019). When provided to maize crops, urea-based nanocomposites, including $ZnSO_4$ or ZnO NCs, in fertilizer stimulated plant development in a nutrient-poor sand. When several fertilizer nanocomposites were applied simultaneously, it improved root morphology characteristics, such as increased root length and surface area, which improved nutrient uptake from soil (Giroto et al., 2022). In a study of cotton plants, zinc NCs in fertilizer improved several physiological parameters, namely chlorophyll content and antioxidant activity, which are indicators of plant quality and quantity (Hussein & Abou-Baker, 2018). Plants treated with foliar applications of Zn NC fertilizer and humic acid markedly increased plant growth and dry biomass (Najafi Vafa et al., 2015). Additionally, the contents of plant growth–promoting hormones were increased with the use of Fe and Zn NC fertilizers (Sharifi, 2016). Layered double hydroxide (LDH) and multiwalled carbon nanotubes (MWCNTs) with zinc have also been explored to improve micronutrient release and distribution. One study on onion plants under arid conditions used MWCNTs as micronutrient distributors and a nutrient stabilizer, which resulted in improved plant growth (Kumar et al., 2018). Nanocomposites of Zn and Al in a layered double-hydroxide matrix maintained the pH level via a controlled release of α-naphthalene acetate, which acted as a plant growth regulator (bin Hussein et al., 2002).

Iron (Fe) is an essential micronutrient for plant growth. It contributes to photosynthesis, chloroplast development, and dark respiration. Iron-deficit plants exhibit reduced photosystems and lipid composition and altered chlorophyll ratios (Alidoust & Isoda, 2013; Ghasemi et al., 2014). *Gum kondagogu*, a natural biopolymer, has been used in a nanocomposite material for mungbean plant growth. This nanocomposite, which includes highly monodispersed Fe nanoparticles and *Gum kondagogu*, has been reported to improve plant growth. The increased radial length and biomass were attributed to increased water uptake that was facilitated by the use of Fe nanoparticles (Raju et al., 2016). Zeolite/Fe_2O_3 nanocomposites synthesized by using low-cost and low-energy natural materials were reported as a fertilizer formulation that improved plant growth and yields (Jahangirian et al., 2020).

Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K)—together referred to as NPK—are required in adequate amount for plants to efficiently reach their genetic yield potentials. NCs have well-known benefits, such as the ease of penetration, that enhance the application of NPK. The increase in the growth of wheat leaves, for example, was achieved by increasing NPK nutrient availability, thanks to a nanosize formulation that penetrated the leaves' stomata via gas exchange, as reported by Abdel-Aziz et al. (2018). Many biopolymers are in the nanocomposite formulations used in the agricultural sector (Kassem et al., 2021; Menossi et al., 2022; Olad et al., 2018; Pimsen et al., 2021). In the exploration of sustainable agricultural practices, chitosan-based nanocomposites (ChNCs) could be ecofriendly alternatives that contribute to plant growth (Jain et al., 2022). Chitosan, a natural polymer extracted from the chitin deacetylation of crustaceans, insects, fungi, etc., is used as one of the types of NPK nanocomposites. Chitosan has a natural affinity for metals, making it an efficient encapsulating agent. Efficient nutrient utilization ensures plant growth and can be achieved by using chitosan-based nanocomposites (Sharma et al., 2022). ChNCs are some of the prime candidates for improving crop growth, crop physiology, and crop protection. ChNCs are often sourced from biofood waste in cost-effective, biodegradable, biocompatible, and benign ways. These formulations regulate plant growth, antimicrobial activities, and stress-inhibitory activities. Recently, researchers designed and tested various recipes involving several types of ChNCs (Sangwan et al., 2023). Overall, ChNCs contributes towards a wide range of enhancements of plant morphology.

However, there are mixed reports about the role of chitosan on the growth of the roots, shoots, and leaves of various plants. One study on the use of chitosan + NPK nanocomposites for the growth of wheat plants in sandy soil reported positive results at harvest along crop and mobilization indices, along with a shorter life cycle (Abdel-Aziz et al., 2016). By using the slow-release method, nanocomposites formed with zeolite and chitosan and combined with sago starch reported to result in better growth indicators. Such nanocomposites also helped in maintaining the water level, proving their use as slow-release fertilizers (Pimsen et al., 2021). A superabsorbent nanocomposite revealed that the slow-release process facilitated water uptake. This nanocomposite was produced by using an Fe and NPK agrochemical formulation based on maize bran and montmorillonite (Gharekhani et al., 2018). In another formulation, poly (vinyl alcohol) + cellulose nanocomposites were developed such that the cellulose nanocrystals were derived from hemp stems through chemical treatments. The poly (vinyl alcohol) + cellulose nanocomposites were used to coat NPK-compound fertilizers by using a fluidized bed-coating machine. Improvements in release behavior and moisture content in soil were reported after using these formulations (Kassem et al., 2021).

2.2 Plant Physiology

Plant physiology parameters include fresh/dry weight, root–shoot ratios, root biomass and shoot biomass. Leaf area, crop yield, the reproductive index, photosynthetic pigment content, and chlorophyll α fluorescence are some of the other important plant physiology parameters (Füzy et al., 2019). Because the inclusion of nanosize minerals as nutrients and stimulants in plant fertilizer strategies has improved the physiological and biochemical attributes of plants, research on the use of nanocomposites for improving plant physiology has accelerated. Additionally, nanoparticles also reduce oxidative damage and improve water and nutrient uptake, resulting in increased crop yields.

Biochar, a charcoal-like substance, is synthesized in a controlled environment by burning the organic waste from agriculture and forestry to reduce contamination and ensure the safe storage of carbon. In the pursuit of increasing of crop yields, the harmful effects of various environmental stresses, such as salinity, must be minimized (Hessini et al., 2019). Any imbalance in the conventional practice of using mineral fertilizers reduces plant growth potential and nutritive quality instead of achieving higher yields (Kumar et al., 2021). Moreover, it worsens soil conditions and pollutes the environment.

Salinity affects plant growth potential, reduces the output of photosynthesis, and adversely impacts water and ion statuses in affected plants. Researchers have aimed to improve plants' salt tolerance under saline conditions by increasing the electron transport rate and reducing sodium accumulation and reactive oxygen species (ROS) generation (Chrysargyris et al., 2019). Salt toxicity leads to stomatal conductivity, which generates high levels of reactive oxygen species (Egamberdieva et al., 2019; Kapoor et al., 2022). This high level of reactive oxygen species disrupts plants' cellular structures and causes cell death. To enable plant survival under saline conditions, ample concentrations of nutrients must be made available to plants; this is because nutrients help regulate physiological pathways under saline stress (Sheldon et al., 2017).

The use of biochar nanocomposites with magnesium and manganese has been reported to increase the contents of potassium, manganese, and magnesium in plant tissues, photosynthetic pigmentation, and leaf water content and to reduce sodium accumulation, together increasing plant biomass when compared with control plants (Ghassemi-Golezani & Farhangi-Abriz, 2021). Nanocomposites such as biochar and metal oxides might compound the benefits of biochar and nanomaterials. Nanocomposites made from a combination of magnesium and manganese metal oxides with biochar improved chlorophyll content, root growth, and the overall productivity of safflowers (Ghassemi-Golezani & Farhangi-Abriz, 2021). This nanocomposite also contributed to maintaining optimal concentrations of nutrients and optimal water content in plant cells and enhanced nutrient absorption rates (Farhangi-Abriz & Ghassemi-Golezani, 2021).

The physiological and biochemical parameters of crops improve with the application of nanocomposites. In the case of sunflowers, a $Fe_3O_4 + H_2O$ biocompatible magnetic nanofluid improved the total chlorophyll content of leaves at a low concentration, namely > 0.75% (Pîrvulescu, et al., 2015). Barley plants were hydroponically subjected to a recipe of Co and Nd doped in Fe nanoparticles that were produced via the sonochemical synthesis method. This resulted in an increase in biomass, chlorophyll content, and carotenoids at certain concentrations (125, 250, 500, and 1000 mg/L); that study concluded that the improvement in plant physiology showed a positive correlation between magnetic nanoparticles (MNPs) and photosynthetic machinery (Tombuloglu et al., 2020). After foliar applications of nanosize TiO_2 ($nTiO_2$), increases in yield, chlorophyll content, carotenoids, and anthocyanin content were reported in maize plants by Morteza et al. and in barley plants by Janmohammadi et al. (Morteza et al., 2013; Janmohammadi et al., 2016). Other studies have reported improvements in the structure of chlorophyll, the ability to capture sunlight, pigment production, ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo) activity, and photosynthesis efficiency after applications of $nTiO_2$ (Gohari et al., 2020; Satti et al., 2022; Yang et al., 2006). A study using perlite NPs and TiO_2/perlite NCs claimed that biologically synthesized NPs were more benign than chemically synthesized NPs. While no significant change in chlorophyll or carotenoid contents was reported in that study, valuable secondary metabolites, such as volatile compounds, hypericin, and pseudohypericin, significantly increased after the treatment using TiO_2/perlite NCs. The experimental steps involved in that study are depicted in Fig. 4.3 (Ebadollahi et al., 2019).

The benefits of Zn and Si nanoparticles could be advantageous to plant physiology (Song & Kim, 2020; Sturikova et al., 2018). A Zn-Si nanocomposite could bring the functionalities of separate phases together. Zn plays a critical role in various crops in that it improves chlorophyll content, plant biomass, and yield quantity. The functionality of Si controlling root to leave transportation of Na^+ ions and increasing the level of K^+ ions in leaves is useful in minimizing the negative impacts of oxidative, salinity, and drought stresses (Naaz et al., 2022; Rastogi et al., 2019).

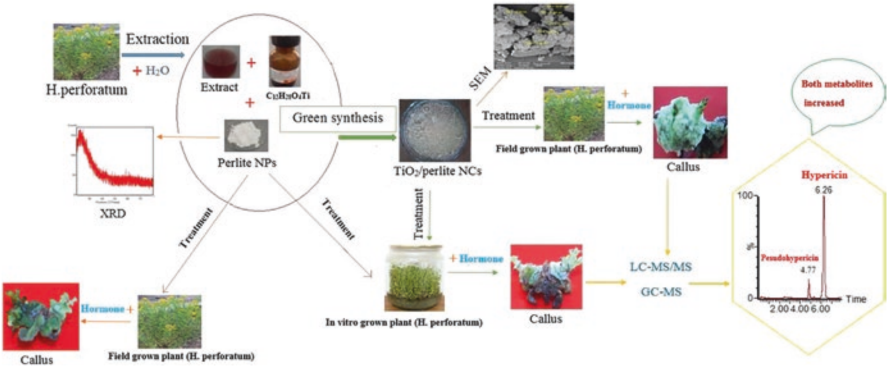

Fig. 4.3 Flowchart showing the role of TiO_2/perlite NCs on the plant physiology of *Hypericum perforatum*. (Reprinted with permission from Ebadollahi et al., 2019)

These features become useful under soil salinity, arid, and semiarid conditions. A foliar spray containing Zn-Si nanocomposites that was used on soybean plants in saline soil that contained plant growth–promoting microbes significantly diminished the detrimental effects of water stress and soil salinity on soybean crop physiology (Osman et al., 2021). The changes to plants after a water application led to deeper root penetration, heavier nodules (according to dry weight), and higher leaf K^+ content. A metal nanocomposite of magnesium and manganese based on biochar was evaluated for soil quality and salt toxicity in safflowers. The study emphasized the role of NCs in enriching plant physiology when the water level of plant tissues was maintained. The NCs affected the required exchangeable sodium concentration in soil and enhanced the nutrient absorption rate of plants. Osmotic stress is a consequence of salinity which reduces the abosorption rate of the plants. A reduction in the osmotic stress was observed after the application of NCs.

Our current gap between food demands and agricultural production requires scientific approaches that bring about uniform seed germination and seedling development to ensure proper crop growth. The process of germination initiated via imbibition—i.e., mature dry seed taking up water from soil moisture—completes the life cycle in a way that lengthens the embryonic axis, typically the radicle, from the seed envelope. The degradation of starch during the germination of crop seeds and the consequent seedling establishment lead to enzymatic actions. α-amylase is the enzyme that initiates the hydrolysis of starch granules naturally synthesized during the germination of seeds. The α-amylase augmentation during seed germination is vital for efficient plant growth. Seed priming is one of the standard modern agricultural practices advantageous for increasing seed germination efficiency, seedling growth, and protection against pathogens (Chakkalakkal et al., 2022). Including NCs in priming, which achieves the slow uptake of intended nutrients to the developing plant, standardizes the antioxidant defense system, leading to enhanced germination competence and plant growth (Szőllősi et al., 2020). Various parameters, such as comparable size, stability, and coatings of nanocomposite materials, are advantageous for plants to take up nutrients through the root epidermis (Zhang et al., 2022a, b). These nanocomposites are bio-altered into their ionic forms and are distributed throughout the rest of the plant parts (Szőllősi et al., 2020). The NCs work as a stimulus in seed germination by reducing seed dormancy, which eventually accelerates the germination rate and seedling development. Reductions in cell division in the apex roots, leading to root shortening, and increases in the levels of lipid peroxidation, leading to chromosomal aberrations and mitotic abnormalities, need to be properly addressed before systematically using NCs.

Crop seed germination is vulnerable to diverse environmental stresses. A nanocomposite recipe that preserves germination activity at desired levels while helping seeds adapt to adverse environmental conditions is needed. Coating reagents in nanocomposites have effectively improved wheat seed germination and subsequent seedling establishment under manifold environmental stresses. The carbon dioxide generated in the process of seed respiration and gradually emitted oxygen may accelerate seed germination activity and reduce germination time. Coating reagents can be critical in water absorption and retention because they effectively absorb carbon dioxide. Nanocomposite materials using natural clays help to establish a suitable soil-moisture-conserving matrix. Supplementing crops with nutrients such as zinc (Zn) and iron (Fe) may also improve moisture retention (Nada & Blumenstein, 2015). This eventually enhances crop yields and quality by improving the physical and biological parameters of soil. A silica and calcium peroxide nanocomposite matrix used as an environmentally friendly seed coating approach for wheat crops maintained high seed germination activity, as reported by Jun Ni et al. (2022). A constant rate of generating hydrogen peroxide at smaller dosages has been recognized as a mechanism for protecting seeds from microbial infection during seed germination and seedling establishment.

2.3 Crop Quantity and Quality

Nanocomposites (NCs) are readily absorbed and internally distributed by plants in such a way that they improve crop quantities and yields. NCs also demonstrate better abilities to provide nutrients because they possess large surface areas, high reactivity rates, compatible pore sizes, and desirable particle morphologies. The antimicrobial characteristics of nanoparticles can be exploited in nanocomposite formulations to protect plants. Bacteria and fungi are the main causes of infestations that lead to various crop diseases. These infections seriously threaten crop growth, reduce crop yields and quality, and can even lead to health risks to humans upon consumption. Metallic nanoparticle-based nanocomposites play significant roles in inhibiting pathogenic bacteria and fungi. More research on metallic nanoparticle-based nanocomposites needs to be carried out to assess the interactions between nanoparticles and pathogens, and the indirect effects of inducing plant susceptibility to infection also needs to be considered. Ferrite materials and their composites have a wide range of applications (Shaikh et al., 2021; Toksha et al., 2008, 2017). Most of the elements, in addition to iron, that are included in ferrite matrices are essential nutrients for plant growth and yields (Shebl et al., 2020). In one study, Mn-Zn nanosize ferrites at varying concentration levels that were applied through the foliar method to squash plants (*Cucurbita pepo L.*) resulted in yield increases as high as 50%, along with increases in organic matter content and total energy in squash leaves (Shebl et al., 2020). In the case of wheat crops, a Ce-Mn ferrite nanocomposite has been reported to improve photosynthesis efficiency and total crop yields. Realizing the potential of NC applications as fertilizers, one study reported increases in the uptakes of Fe and Mn micronutrients in plant shoots (Zarinkoob et al., 2021).

Crop quantity varies as a function of the size of nanoparticles, their compositions, and their concentrations. It also depends on the physical and chemical properties of the NCs and the targeted plant species. Fertilization efficiency is critically affected by changes in pore size distribution. Thus, the choice of synthesis method becomes important because it controls the properties of NC fertilizer, such as surface morphology, pore structure, and particle size and shape. This in turn determines crop yields. When nanocomposite fertilizers with chitosan and NPK fertilizers are used in low concentrations under clayey and sandy soil conditions, they have been reported to increase plant growth rates in wheat crops (Abdel-Aziz et al., 2016). The important characteristics of crop yields include seed weight, seed yield, seed height, and the number of branches produced. One study reported that crop quantity and quality were ensured through growth-promoting action and the simultaneous application of Fe + Zn with NPK (Drostkar et al., 2016). This beneficial effect on crop quantity and quality contributes to cumulative growth hormone production and metabolic process augmentation. In one study, seed treatments of Fe_3O_4–urea nanocomposites on rice plants under hydroponic conditions resulted in enhanced growth and yields (Guha et al., 2022). The NCs enhanced photosynthetic efficiency and nitrogen infusion by making the nitrogen and iron readily available to the plant. The slow release of urea achieved through these NCs improved the nitrogen use efficiency of the plant.

The yield and subsequent storage of crops must be considered because crops are prone to growing mildew, owing to their rich nutrition (Li et al., 2021; Rodríguez-Félix et al., 2021). Pathogens such as mildew lead to declines in quality and germination rate and can even harm human health (Wang et al., 2020; Wawrzyniak et al., 2018). Crops that have relatively large embryos easily absorb moisture and carry large numbers of bacteria. This makes them susceptible to producing pathogenic microorganisms. Postharvest moisture content provides a suitable growth environment for microorganisms during transportation and storage. This leads to the development and reproduction of pathogenic microorganisms and causes safety problems such as the mildew and excessive mycotoxins (Kimanya, 2015). The quality parameters of a crop include its color, taste, nutrition level, and processing characteristics. Moreover, seeds lose their reproductive value with the excessive growth of microorganisms, which hampers the germination rate (Walker et al., 2018). Combinations of fertilizer NCs and pesticide NCs are parts of recent approaches used to maximize plant growth potentials. Such nanocomposites are synthesized with a multiple target approach of sustained foliar retention weeding and providing nourishment to the plants. Yanzheng Ji et al. reported one such nanocomposite involving zinc, mesoporous silica, and

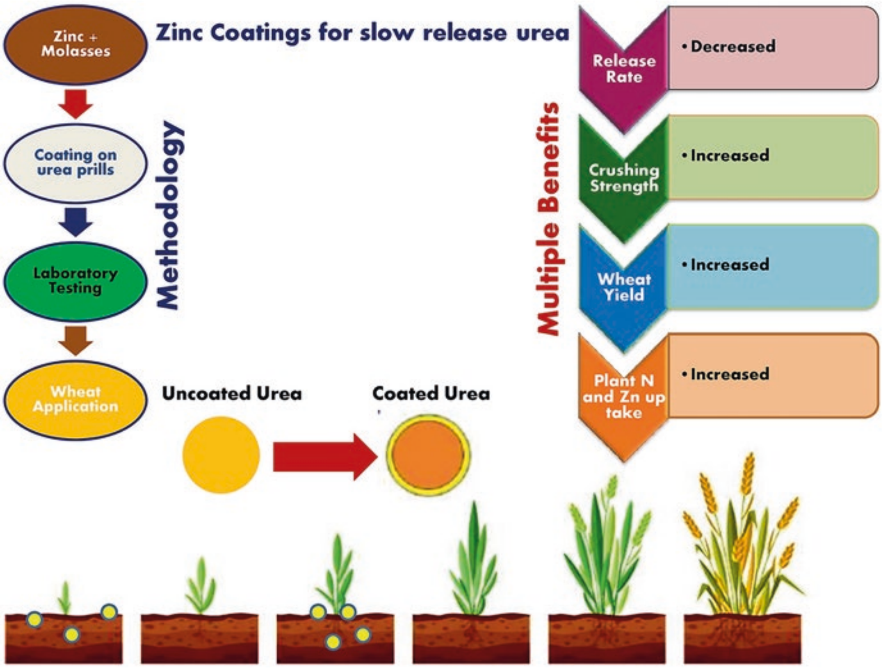

Fig. 4.4 Flowchart of steps for using nanosize zinc coatings to enhance wheat crop yields. (Reprinted with permission from Beig et al., 2022)

polydopamine working as combinations of pesticide NCs and fertilizer NCs (Ji et al., 2020). Nanocomposites used to implement or modify a slow-release mechanism has been recently explored (Dimkpa et al., 2022; Olad et al., 2018). Nano-bentonite supplemented with Zn and ZnO NPs formed a nanocomposite that was encapsulated in stearic acid, paraffin wax, and oil. A coating material binding the Zn and N achieved a slow-release mechanism, thus showing the nano-bentonite to be an ecofriendly and cost-effective material (Umar et al., 2022). The dual role of zinc as a source of micronutrients and a coating material of slow-release urea was reported by Beig et al. (2022). That study reported that the nanosize zinc coating was more effective in increasing N uptake and Zn uptake in wheat crops, resulting in higher yields compared with using bulk zinc coatings. The steps to follow when using nanosize zinc coatings to improve wheat crop yields are listed in Fig. 4.4.

3 Plant Sustainability

The overall wellbeing of crops is vital for food security. In any country's economy, agriculture creates jobs, increases GDP, and provides food, feed, and biofuels. Efforts to maintain the current rate of crop yields are failing to meet global demands.

There is currently at least a 15% gap between the global demand for agricultural products and the crop yields across the globe (Zhao et al., 2022). That crops fall victim to plant diseases and pests only exacerbates the food scarcity problem. On a global scale, the estimated average rates of crop losses caused by pathogens and by pests are 14% and 32%, respectively, for wheat, rice, maize, soybean, and potato crops (OECD-FAO, 2022). The agricultural losses due to pests amount to USD 36 billion annually in India alone (Dhaliwal et al., 2015). Age-old practices, such as tillage, crop rotation, and polycultures, and new practices, such as genetically modifying plants, have been tried and have worked to certain extents at reducing losses from disease outbreaks. Limitations on the availability of arable land and challenges facing maintaining the quality of the environment are the main concerns with these approaches. Moreover, crops may suffer from problems such as lower nutrition values, toxicity, immunosuppression, and allergic reactions (FAO-UN, 2022). In this situation, stable nanocomposites with novel properties, such as cation-exchange capacity and complexation, elevated reactivity, unusual structural phases, large ion-adsorption ratios, and the ability to aggregate, can be effectively used. Polysaccharide nanocomposites have been explored in agricultural research for sustainability (Gamage et al., 2022). These nanocomposites include a wide range of formulations, such as biopolymers, nanosize cellulose, chitin, and clay (Ge et al., 2018). Sathiyanarayanan Anusuya et al. reported the antifungal activity of β-d-glucan nanoparticles against *P. aphanidermatum*, a pathogenic fungus that distresses many prominent greenhouse crops and field crops (Anusuya & Sathiyabama, 2014). A review of the glucan biopolymer was updated by Somnath Chavanke et al., who elaborated on its effective use in mitigating the effects of climate change on crop plants by enhancing their immunity levels (Chavanke et al., 2022).

Crop storage is a pressing issue in that all efforts made to reduce hunger by following sustainable agricultural practices have not worked. The limited shelf life of crops and food waste together account for the one-third of food that is produced but not consumed. Biologically sourced multifunctional nanocomposites can be effective in addressing these concerns because they can reduce the rate of food decay by retarding ripening, reducing dehydration, and preventing microbial infections. A sustainable nanocomposite including inexpensive or waste materials such as egg-derived polymers and cellulose nanomaterials was reported by Seohui Jung et al. The food coating was palatable and washable (Jung et al., 2020).

Nanocomposites also contribute to plants by developing sensors for crop pathogen detection and mitigating environmental stresses, both of which help promote crop sustainability (Kumar et al., 2023). Crop diseases reduce physiological growth potentials and yields, causing around 40% of crop yields to be lost every year and might destroy the whole crop (Nagarajan, 2007). Crop diseases are the main challenges to overcome in achieving high yields and healthy crops. Different crops are susceptible to one or more specific diseases, hampering their quality and yields. *Fusarium* head blight (FHB) is a major disease affecting wheat and barley crops, causing as much as 50% of crop yields to be lost (Leplat et al., 2013). *Fusarium* head blight disease causes *F. graminearum* to survive for several years in soil or on dead organic matter, particularly crop residues. Its dangers are multifold because it adapts to a wide range of environmental conditions and produces extracellular enzymes that feed on diverse crop residues. Protection or resistance against pathogenic fungi or bacteria could be achieved by using nanocomposites. Graphene oxide (GO) and silver nanocomposites have shown threefold and sevenfold surges in inhibition efficiency, even at relatively low concentrations, compared to using silver and GO suspensions alone (Chen et al., 2016). Plant diseases such as *Fusarium solani* root rot and wilt diseases occur in many plants, such as soybeans, tomatoes, and peppers. While *Fusarium* root rot causes seedling stunting, root decay, stem staining, and plant death, wilt diseases disrupt water flow in the xylem, causing leaves to wilt and rapidly killing affected plants. Abeid et al. reported copper oxide–coated GO nanosheets to be effective against such diseases (El-Abeid et al., 2020).

Rice is one of the crops that is widely consumed as an essential food worldwide. Rice crops suffer numerous biotic stressors, including microbial infections, pests, and weeds. Temoor Ahmed et al. reported that the use of chitosan-iron nanocomposites controlled a bacterial leaf blight disease in rice crops by modifying plant resistance to this pathogen and improved the nutritional values of those crops (Ahmed et al., 2022). The *Plasmopara viticola* pathogen causes downy mildew disease in grapevine plants. Xiuping Wang et al. reported that GO-Fe_3O_4 nanocomposites were highly effective in treating grapevine plant infections (Wang et al., 2017). According to the above literature, there is a wide scope for research to be conducted on NCs in the fields of plant diseases and plant sustainability.

4 Conclusion

This chapter emphasized the need to study nanocomposite fertilizers. A novel overview of vital crop parameters, such as plant growth, plant physiology, and crop quantity and quality, was presented. Using NCs as nanofertilizers for the enhancement of bio-factors, NC–plant interactions, the safety of using NCs on plants, and NCs' activities in attenuating the adverse effects of abiotic stresses and heavy metal toxicities were discussed. In this context, the toxic effects of NCs on crops, such as those on crop cell structures that increase the oxidative stress indicators, remain major concerns to address. As supported by recent research publications, the conventional benefits of composites, such as enabling the product to meet nutritional requirements, are also available in the case of nanocomposite fertilizers. Improvements in the delivery mechanisms of fertilizers and slowly releasing micronutrients are among the primary benefits of using nanocomposite fertilizers. NCs are vital to reducing the use of conventional fertilizers and consequently their averse environmental effects. NCs are crucial in alleviating abiotic stresses and heavy metal toxicity. Nanocomposite formulations allow the controlled release and targeted delivery of nutrients, reducing nutrient losses. Nanocomposite formulations also positively contribute to increasing parameters such as solubility, dispersion, nutrient uptake, and nutrient availability. Plant responses to the NCs varies depending on the type of plant species, their growth stages, and the nature of the nanocomposite. This chapter laid out the role of nanocomposites in improving the wellbeing of crop, as alternatives to conventional fertilizers.

References

Abd El-Aziz, M. E., Morsi, S. M. M., Salama, D. M., Abdel-Aziz, M. S., Abd Elwahed, M. S., Shaaban, E. A., & Youssef, A. M. (2019). Preparation and characterization of chitosan/polyacrylic acid/copper nanocomposites and their impact on onion production. *International Journal of Biological Macromolecules, 123*, 856–865.

Abdel Maksoud, M. I. A., Bekhit, M., El-Sherif, D. M., Sofy, A. R., & Sofy, M. R. (2022). Gamma radiation-induced synthesis of a novel chitosan/silver/Mn-Mg ferrite nanocomposite and its impact on cadmium accumulation and translocation in brassica plant growth. *International Journal of Biological Macromolecules, 194*, 306–316.

Abdel-Aziz, H. M. M., Hasaneen, M. N. A., & Omer, A. M. (2016). Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Spanish Journal of Agricultural Research, 14*, e0902–e0902.

Abdel-Aziz, H., Hasaneen, M., & Omer, A. (2018). Foliar application of nano chitosan NPK fertilizer improves the yield of wheat plants grown on two different soils. *The Egyptian Journal of Experimental Biology (Botany), 14*, 1.

Achari, G. A., Ramesh, R. (2019). Colonization of Eggplant by Endophytic Bacteria Antagonistic to Ralstonia solanacearum, the Bacterial Wilt Pathogen. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 89, 585–593.

Ahmed, T., Noman, M., Luo, J., Muhammad, S., Shahid, M., Ali, M. A., et al. (2021). Bioengineered chitosan-magnesium nanocomposite: A novel agricultural antimicrobial agent against Acidovorax oryzae and Rhizoctonia solani for sustainable rice production. *International Journal of Biological Macromolecules, 168*, 834–845.

Ahmed, T., Noman, M., Jiang, H., Shahid, M., Ma, C., Wu, Z., et al. (2022). Bioengineered chitosan-iron nanocomposite controls bacterial leaf blight disease by modulating plant defense response and nutritional status of rice (Oryza sativa L.). *Nano Today, 45*, 101547.

Alidoust, D., & Isoda, A. (2013). Effect of γFe2O3 nanoparticles on photosynthetic characteristic of soybean (Glycine max (L.) Merr.): Foliar spray versus soil amendment. *Acta Physiologiae Plantarum, 35*, 3365–3375.

Amer, A., Ghoneim, M., Shoala, T., & Mohamed, H. I. (2021). Comparative studies of eco-friendly compounds like humic acid, salicylic, and glycyrrhizic acids and their nanocomposites on French basil (Ocimum basilicum L. cv. Grand verde). *Environmental Science and Pollution Research International, 28*, 47196–47212.

Anusuya, S., & Sathiyabama, M. (2014). Preparation of β-d-glucan nanoparticles and its antifungal activity. *International Journal of Biological Macromolecules, 70*, 440–443.

Attia, M. S., El-Sayyad, G. S., Abd Elkodous, M., Khalil, W. F., Nofel, M. M., Abdelaziz, A. M., et al. (2021). Chitosan and EDTA conjugated graphene oxide antinematodes in eggplant: Toward improving plant immune response. *International Journal of Biological Macromolecules, 179*, 333–344.

Aziz, M. Z., Yaseen, M., Abbas, T., Naveed, M., Mustafa, A., Hamid, Y., et al. (2019). Foliar application of micronutrients enhances crop stand, yield and the biofortification essential for human health of different wheat cultivars. *Journal of Integrative Agriculture, 18*, 1369–1378.

Batista, P. F., Müller, C., Merchant, A., Fuentes, D., de Oliveira Silva-Filho, R., da Silva, F. B., & Costa, A. C. (2020). Biochemical and physiological impacts of zinc sulphate, potassium phosphite and hydrogen sulphide in mitigating stress conditions in soybean. *Physiologia Plantarum, 168*, 456–472.

Beig, B., Niazi, M. B. K., Jahan, Z., Zia, M., Shah, G. A., Iqbal, Z., & Douna, I. (2022). Facile coating of micronutrient zinc for slow release urea and its agronomic effects on field grown wheat (Triticum aestivum L.). *Science of the Total Environment, 838*, 155965.

Beyer, P. (2010). Golden Rice and 'Golden' crops for human nutrition. *New Biotechnology, 27*, 478–481.

bin Hussein, M. Z., Zainal, Z., Yahaya, A. H., & Foo, D. W. V. (2002). Controlled release of a plant growth regulator, α-naphthaleneacetate from the lamella of Zn–Al-layered double hydroxide nanocomposite. *Journal of Controlled Release, 82*, 417–427.

Carvalho, S. M. P., & Vasconcelos, M. W. (2013). Producing more with less: Strategies and novel technologies for plant-based food biofortification. *Food Research International, 54*, 961–971.

Chakkalakkal, N. D., Thomas, M., Chittillapilly, P. S., Sujith, A., & Anjali, P. D. (2022). Electrospun polymer nanocomposite membrane as a promising seed coat for controlled release of agrichemicals and improved germination: Towards a better agricultural prospect. *Journal of Cleaner Production, 377*, 134479.

Chakraborty, R., Mukhopadhyay, A., Paul, S., Sarkar, S., Mukhopadhyay, R. (2023). Nanocomposite-based smart fertilizers: A boon to agricultural and environmental sustainability. *Science of The Total Environment, 863*, 160859.

Chavanke, S. N., Penna, S., & Dalvi, S. G. (2022). β-Glucan and its nanocomposites in sustainable agriculture and environment: An overview of mechanisms and applications. *Environmental Science and Pollution Research, 29*, 80062–80087.

Chen, J., Sun, L., Cheng, Y., Lu, Z., Shao, K., Li, T., et al. (2016). Graphene oxide-silver nanocomposite: Novel agricultural antifungal agent against *Fusarium graminearum* for crop disease prevention. *ACS Applied Materials & Interfaces, 8*, 24057–24070.

Chrysargyris, A., Papakyriakou, E., Petropoulos, S. A., & Tzortzakis, N. (2019). The combined and single effect of salinity and copper stress on growth and quality of Mentha spicata plants. *Journal of Hazardous Materials, 368*, 584–593.

Chrysargyris, A., Höfte, M., Tzortzakis, N., Petropoulos, S. A., & Di Gioia, F. (2022). Editorial: Micronutrients: The borderline between their beneficial role and toxicity in plants. *Frontiers in Plant Science, 13*, 840624.

De Steur, H., Mehta, S., Gellynck, X., & Finkelstein, J. L. (2017). GM biofortified crops: Potential effects on targeting the micronutrient intake gap in human populations. *Current Opinion in Biotechnology, 44*, 181–188.

Dhaliwal, G. S., Jindal, V., & Mohindru, B. (2015). Crop losses due to insect pests: Global and Indian Scenario. *Indian Journal of Entomology, 77*, 165.

Dhaliwal, S. S., Sharma, V., Shukla, A. K., Kaur, J., Gupta, R. K., Verma, V., et al. (2023). Interactive effect of land use systems on depth-wise soil properties and micronutrients minerals in North-Western, India. *Heliyon, 9*(2), e13591.

Dimkpa, C. O., Campos, M. G. N., Fugice, J., Glass, K., Ozcan, A., Huang, Z., et al. (2022). Synthesis and characterization of novel dual-capped Zn–urea nanofertilizers and application in nutrient delivery in wheat. *Environmental Science: Advances, 1*, 47–58.

Drostkar, E., Talebi, R., & Kanouni, H. (2016). *Foliar application of Fe, Zn and NPK nanofertilizers on seed yield and morphological traits in chickpea under rainfed condition*. Retrieved from https://www.semanticscholar.org/paper/Foliar-application-of-Fe%2C-Zn-and-NPK-on-seed-yield-Drostkar-Talebi/bd1aeab33ac893f2e78651e6aa7850c634d21fcd

Durgude, S. A., Ram, S., Kumar, R., Singh, S. V., Singh, V., Durgude, A. G., Pramanick, B., Maitra, S., Gaber, A., & Hossain, A. (2022). Plant-based nanomaterials: Raw materials, techniques, and applications in food, agriculture, and health. *Journal of Nanomaterials*, 5120307.

Dutta, P., Kumari, A., Mahanta, M., Biswas, K. K., Dudkiewicz, A., Thakuria, D., ... & Mazumdar, N. (2022). Advances in nanotechnology as a potential alternative for plant viral disease management. *Frontiers in Microbiology, 13,* 935193.

Ebadollahi, R., Jafarirad, S., Kosari-Nasab, M., & Mahjouri, S. (2019). Effect of explant source, perlite nanoparticles and TiO2/perlite nanocomposites on phytochemical composition of metabolites in callus cultures of Hypericum perforatum. *Scientific Reports, 9*, 12998.

Egamberdieva, D., Wirth, S., Bellingrath-Kimura, S. D., Mishra, J., & Arora, N. K. (2019). Salt-tolerant plant growth promoting rhizobacteria for enhancing crop productivity of saline soils. *Frontiers in Microbiology, 10*. Retrieved from https://www.frontiersin.org/articles/10.3389/fmicb.2019.02791

El-Abeid, S. E., Ahmed, Y., Daròs, J.-A., & Mohamed, M. A. (2020). Reduced graphene oxide nanosheet-decorated copper oxide nanoparticles: A potent antifungal nanocomposite against *Fusarium* root rot and wilt diseases of tomato and pepper plants. *Nanomaterials, 10*, 1001.

El-Kahky, D., Attia, M., Easa, S. M., Awad, N. M., & Helmy, E. A. (2021). Interactive effects of biosynthesized nanocomposites and their antimicrobial and cytotoxic potentials. *Nanomaterials, 11*(4), 903.

Erenstein, O., Poole, N., & Donovan, J. (2022). Role of staple cereals in human nutrition: Separating the wheat from the chaff in the infodemics age. *Trends in Food Science & Technology, 119*, 508–513.

FAO-UN. (2022). *Genetically modified crops: Safety, benefits, risks and global status |Policy Support and Governance| Food and Agriculture Organization of the United Nations*. FAO-UN.

Farhangi-Abriz, S., & Ghassemi-Golezani, K. (2021). Changes in soil properties and salt tolerance of safflower in response to biochar-based metal oxide nanocomposites of magnesium and manganese. *Ecotoxicology and Environmental Safety, 211*, 111904.

Füzy, A., Kovács, R., Cseresnyés, I., Parádi, I., Szili-Kovács, T., Kelemen, B., et al. (2019). Selection of plant physiological parameters to detect stress effects in pot experiments using principal component analysis. *Acta Physiologiae Plantarum, 41*, 56.

Gamage, A., Thiviya, P., Mani, S., Ponnusamy, P. G., Manamperi, A., Evon, P., et al. (2022). Environmental properties and applications of biodegradable starch-based nanocomposites. *Polymers, 14*, 4578.

García-Ovando, A. E., Ramírez Piña, J. E., Esquivel Naranjo, E. U., Cervantes Chávez, J. A., & Esquivel, K. (2022). Biosynthesized nanoparticles and implications by their use in crops: Effects over physiology, action mechanisms, plant stress responses and toxicity. *Plant Stress, 6*, 100109.

Ge, S., Li, M., Ji, N., Liu, J., Mul, H., Xiong, L., & Sun, Q. (2018). Preparation of a strong gelatin–short linear glucan nanocomposite hydrogel by an in situ self-assembly process. *Journal of Agricultural and Food Chemistry, 66*, 177–186.

Gharekhani, H., Olad, A., & Hosseinzadeh, F. (2018). Iron/NPK agrochemical formulation from superabsorbent nanocomposite based on maize bran and montmorillonite with functions of water uptake and slow-release fertilizer. *New Journal of Chemistry, 42*, 13899–13914.

Ghasemi, S., Khoshgoftarmanesh, A. H., Afyuni, M., & Hadadzadeh, H. (2014). Iron(II)–amino acid chelates alleviate salt-stress induced oxidative damages on tomato grown in nutrient solution culture. *Scientia Horticulturae, 165*, 91–98.

Ghassemi-Golezani, K., & Farhangi-Abriz, S. (2021). Biochar-based metal oxide nanocomposites of magnesium and manganese improved root development and productivity of safflower (Carthamus tinctorius L.) under salt stress. *Rhizosphere, 19*, 100416.

Giroto, A. S., do Valle, S. F., Guimarães, G. G. F., Wuyts, N., Ohrem, B., Jablonowski, N. D., et al. (2022). Zinc loading in urea-formaldehyde nanocomposites increases nitrogen and zinc micronutrient fertilization efficiencies in poor sand substrate. *Science of the Total Environment, 841*, 156688.

Gohari, G., Mohammadi, A., Akbari, A., Panahirad, S., Dadpour, M. R., Fotopoulos, V., & Kimura, S. (2020). Titanium dioxide nanoparticles (TiO2 NPs) promote growth and ameliorate salinity stress effects on essential oil profile and biochemical attributes of Dracocephalum moldavica. *Scientific Reports, 10*, 912.

Guha, T., Gopal, G., Mukherjee, A., & Kundu, R. (2022). Fe3O4-urea nanocomposites as a novel nitrogen fertilizer for improving nutrient utilization efficiency and reducing environmental pollution. *Environmental Pollution, 292*, 118301.

Hessini, K., Issaoui, K., Ferchichi, S., Saif, T., Abdelly, C., Siddique, K. H. M., & Cruz, C. (2019). Interactive effects of salinity and nitrogen forms on plant growth, photosynthesis and osmotic adjustment in maize. *Plant Physiology and Biochemistry, 139*, 171–178.

Hussein, M. M., & Abou-Baker, N. H. (2018). The contribution of nano-zinc to alleviate salinity stress on cotton plants. *Royal Society Open Science, 5*, 171809.

Jahangirian, H., Rafiee-Moghaddam, R., Jahangirian, N., Nikpey, B., Jahangirian, S., Bassous, N., et al. (2020). Green synthesis of zeolite/Fe_2O_3 nanocomposites: Toxicity & cell proliferation assays and application as a smart iron nanofertilizer. *International Journal of Nanomedicine, 15*, 1005–1020.

Jain, T., Srivastava, K., Kumar, S., & Dutta, P. K. (2022). Chapter 6—Current and future prospects of chitosan-based nanomaterials in plant protection and growth. In S. Kumar & S. V. Madihally (Eds.), *Role of chitosan and chitosan-based nanomaterials in plant sciences* (pp. 143–163). Academic.

Jakhar, A. M., Aziz, I., Kaleri, A. R., Hasnain, M., Haider, G., Ma, J,. Abideem, Z. (2022). Nano-fertilizers: A sustainable technology for improving crop nutrition and food security. *NanoImpact, 27*, 100411.

Jampílek, J., & Kráľová, K. (2022). Chapter 13—Impact of copper-based nanoparticles on economically important plants. In K. A. Abd-Elsalam (Ed.), *Copper nanostructures: Next-generation of agrochemicals for sustainable agroecosystems* (pp. 293–339). Elsevier.

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

Jha, A., Pathania, D., Sonu, et al. (2023). Panorama of biogenic nano-fertilizers: A road to sustainable Agriculture. *Environmental Research, 235*, 116456.

Ji, Y., Huang, M., Yan, J., Qi, T., Li, T., Liu, Y., et al. (2020). Adhesive nanocomposite for prolonging foliar retention and synergistic weeding and nourishing. *Advanced Sustainable Systems, 4*, 2000010.

Jung, S., Cui, Y., Barnes, M., Satam, C., Zhang, S., Chowdhury, R. A., et al. (2020). Multifunctional bio-nanocomposite coatings for perishable fruits. *Advanced Materials, 32*, 1908291.

Kapoor, P., Dhaka, R. K., Sihag, P., Mehla, S., Sagwal, V., Singh, Y., et al. (2022). Nanotechnology-enabled biofortification strategies for micronutrients enrichment of food crops: Current understanding and future scope. *NanoImpact, 26*, 100407.

Kassem, I., Ablouh, E.-H., El Bouchtaoui, F.-Z., Kassab, Z., Khouloud, M., Sehaqui, H., et al. (2021). Cellulose nanocrystals-filled poly (vinyl alcohol) nanocomposites as waterborne coating materials of NPK fertilizer with slow release and water retention properties. *International Journal of Biological Macromolecules, 189*, 1029–1042.

Kheir, A. M. S., Abouelsoud, H. M., Hafez, E. M., & Ali, O. A. M. (2019). Integrated effect of nano-Zn, nano-Si, and drainage using crop straw–filled ditches on saline sodic soil properties and rice productivity. *Arabian Journal of Geosciences, 15*, 1–8.

Kimanya, M. E. (2015). The health impacts of mycotoxins in the eastern Africa region. *Current Opinion in Food Science, 6*, 7–11.

Koondhar, M. A., Aziz, N., Tan, Z., Yang, S., Raza Abbasi, K., & Kong, R. (2021). Green growth of cereal food production under the constraints of agricultural carbon emissions: A new insights from ARDL and VECM models. *Sustainable Energy Technologies and Assessments, 47*, 101452.

Kumar, P., & Sharma, P. K. (2020). Soil salinity and food security in India. *Frontiers in Sustainable Food Systems, 4*. Retrieved from https://www.frontiersin.org/articles/10.3389/fsufs.2020.533781

Kumar, V., Sachdev, D., Pasricha, R., Maheshwari, P. H., & Taneja, N. K. (2018). Zinc-supported multiwalled carbon nanotube nanocomposite: A synergism to micronutrient release and a smart distributor to promote the growth of onion seeds in arid conditions. *ACS Applied Materials & Interfaces, 10*, 36733–36745.

Kumar, A., Singh, S., Mukherjee, A., Rastogi, R. P., & Verma, J. P. (2021). Salt-tolerant plant growth–promoting Bacillus pumilus strain JPVS11 to enhance plant growth attributes of rice and improve soil health under salinity stress. *Microbiological Research, 242*, 126616.

Kumar, A., Kaur, H., Choudhary, A., Mehta, K., Chattopadhyay, A., & Mehta, S. (2023). Chapter 7—Role of nanocomposites in sustainable crop plants' growth and production. In A. Husen (Ed.), *Engineered nanomaterials for sustainable agricultural production, soil improvement and stress management* (pp. 161–181). Academic.

Kwas, M., Paccagnini, A., & Rubaszek, M. (2022). Common factors and the dynamics of cereal prices. A forecasting perspective. *Journal of Commodity Markets, 28*, 100240.

Leplat, J., Friberg, H., Abid, M., & Steinberg, C. (2013). Survival of *Fusarium graminearum*, the causal agent of *Fusarium* head blight. A review. *Agronomy for Sustainable Development, 33*, 97–111.

Li, S., Tian, Y., Jiang, P., Lin, Y., Liu, X., & Yang, H. (2021). Recent advances in the application of metabolomics for food safety control and food quality analyses. *Critical Reviews in Food Science and Nutrition, 61*, 1448–1469.

Liang, D., Wang, Y., Shi, H., Luo, Z., Quirino, R. L., Lu, Q., & Zhang, C. (2022). Controllable release fertilizer with low coating content enabled by superhydrophobic castor oil-based polyurethane nanocomposites prepared through a one-step synthetic strategy. *Industrial Crops and Products, 189*, 115803.

Liu, B., Mu, L., Zhang, J., Han, X., & Shi, H. (2020). TiO2/Cu2(OH)2CO3 nanocomposite as efficient antimicrobials for inactivation of crop pathogens in agriculture. *Materials Science and Engineering: C, 107*, 110344.

Lohmousavi, S. M., Abad, H. H. S., Noormohammadi, G., & Delkhosh, B. (2020). Synthesis and characterization of a novel controlled release nitrogen-phosphorus fertilizer hybrid nanocomposite based on banana peel cellulose and layered double hydroxides nanosheets. *Arabian Journal of Chemistry, 13*, 6977–6985.

Mary Isabella Sonali, J., Kavitha, R., Kumar, P. S., Rajagopal, R., Gayathri, K. V., Ghfar, A. A., & Govindaraju, S. (2022). Application of a novel nanocomposite containing micro-nutrient solubilizing bacterial strains and CeO2 nanocomposite as bio-fertilizer. *Chemosphere, 286*, 131800.

Mengel, K., Kirkby, E. A., Kosegarten, H., & Appel, T. (Eds.). (2001). *Principles of plant nutrition*. Springer Netherlands.

Menossi, M., Casalongué, C., & Alvarez, V. A. (2022). Bio-nanocomposites for modern agricultural applications. In S. Mallakpour & C. M. Hussain (Eds.), *Handbook of consumer nanoproducts* (pp. 1201–1237). Springer Nature.

Merghany, M. M., Abdelgawad, K. F., Tawfic, G. A., & Ahmed, S. S. (2019). Yield, quality and leaves anatomy structure of spring onion sprayed by nanocomposite to control Thrips tabaci. *Plant Archives, 19*, 1839–1849.

Morteza, E., Moaveni, P., Farahani, H. A., & Kiyani, M. (2013). Study of photosynthetic pigments changes of maize (Zea mays L.) under nano Tio2 spraying at various growth stages. *Springerplus, 2*, 247.

Naaz, H., Rawat, K., Saffeullah, P., & Umar, S. (2022). Silica nanoparticles synthesis and applications in agriculture for plant fertilization and protection: A review. *Environmental Chemistry Letters, 21*(1), 539–559. https://doi.org/10.1007/s10311-022-01515-9

Nada, W. M., & Blumenstein, O. (2015). Characterization and impact of newly synthesized superabsorbent hydrogel nanocomposite on water retention characteristics of sandy soil and grass seedling growth. *International Journal of Soil Science, 10*, 153–165.

Nagarajan, S. (2007). Plant diseases in India and their control. In *Ciba foundation symposium 177—Crop protection and sustainable agriculture* (pp. 208–227). Wiley.

Najafi Vafa, Z., Sirousmehr, A., Ghanbari, A., Khammari, I., & Falahi, N. (2015). Effects of nano zinc and humic acid on quantitative and qualitative characteristics of savory (Satureja hortensis L.). *Journal of BioScience and Biotechnology*. https://doi.org/10.12692/ijb/6.3.124-136 do Nascimento, L. Á., Abhilasha, A., Singh, J., Elias, M. C., & Colussi, R. (2022). Rice germination and its impact on technological and nutritional properties: A review. *Rice Science, 29*, 201–215.

Neitzel, I., Mochalin, V., & Gogotsi, Y. (2012). Chapter 13—Advances in surface chemistry of nanodiamond and nanodiamond–Polymer composites. In O. A. Shenderova & D. M. Gruen (Eds.), *Ultananocrystalline diamond* (2nd ed., pp. 421–456). William Andrew Publishing.

Ni, J., Hu, H., & Wu, L. (2022). Fabrication of calcium peroxide into amphiphilic nest-like attapulgite/SiO2 as a seed coating nanocomposite of wheat that confers resistance to multiple environmental stresses. *ACS Agricultural Science & Technology, 2*, 1300–1310.

Nokandeh, S., Ramezani, M., & Gerami, M. (2021). The physiological and biochemical responses to engineered green graphene/metal nanocomposites in Stevia rebaudiana. *Journal of Plant Biochemistry and Biotechnology, 30*, 579–585.

OECD-FAO. (2022). *OECD-FAO agricultural outlook 2022–2031 (No. 20.500.12592/vn963f)*. FAO: Food and Agriculture Organization of the United Nations.

Olad, A., Zebhi, H., Salari, D., Mirmohseni, A., & Reyhani Tabar, A. (2018). Slow-release NPK fertilizer encapsulated by carboxymethyl cellulose-based nanocomposite with the function of water retention in soil. *Materials Science and Engineering: C, 90*, 333–340.

Osman, H. S., Gowayed, S. M., Elbagory, M., Omara, A. E.-D., El-Monem, A. M. A., Abd El-Razek, U. A., & Hafez, E. M. (2021). Interactive impacts of beneficial microbes and Si-Zn nanocomposite on growth and productivity of soybean subjected to water deficit under salt-affected soil conditions. *Plants, 10*, 1396.

Perfileva, A. I., Moty'leva, S. M., Klimenkov, I. V., Arsent'ev, K. Y., Graskova, I. A., Sukhov, B. G., & Trofimov, B. A. (2017). Development of antimicrobial nano-selenium biocomposite for protecting potatoes from bacterial phytopathogens. *Nanotechnologies in Russia, 12*, 553–558.

Pimsen, R., Porrawatkul, P., Nuengmatcha, P., Ramasoot, S., & Chanthai, S. (2021). Efficiency enhancement of slow release of fertilizer using nanozeolite–chitosan/sago starch-based biopolymer composite. *Journal of Coatings Technology and Research, 18*, 1321–1332.

Pîrvulescu, M., Sala, F., Boldea, M. (2015). Variation of chlorophyll content in sunflower under the influence of magnetic nanofluids. *AIP Conference Proceedings, 1648*, 670009.

Poole, N., Donovan, J., & Erenstein, O. (2021). Viewpoint: Agri-nutrition research: Revisiting the contribution of maize and wheat to human nutrition and health. *Food Policy, 100*, 101976.

Raju, D., Mehta, U. J., & Beedu, S. R. (2016). Biogenic green synthesis of monodispersed gum kondagogu (Cochlospermum gossypium) iron nanocomposite material and its application in germination and growth of mung bean (Vigna radiata) as a plant model. *IET Nanobiotechnology, 10*, 141–146.

Rastogi, A., Tripathi, D. K., Yadav, S., Chauhan, D. K., Živčák, M., Ghorbanpour, M., et al. (2019). Application of silicon nanoparticles in agriculture. *3 Biotech, 9*, 90.

Rodríguez-Félix, F., López-Cota, A. G., Moreno-Vásquez, M. J., Graciano-Verdugo, A. Z., Quintero-Reyes, I. E., Del-Toro-Sánchez, C. L., & Tapia-Hernández, J. A. (2021). Sustainable-green synthesis of silver nanoparticles using safflower (Carthamus tinctorius L.) waste extract and its antibacterial activity. *Heliyon, 7*(4), e06923. https://doi.org/10.1016/j.heliyon.2021.e06923

Sahoo, S. K., Panigrahi, G. K., Sahoo, A., Pradhan, A. K., & Dalbehera, A. (2021). Bio-hydrothermal synthesis of ZnO–ZnFe2O4 nanoparticles using Psidium guajava leaf extract: Role in waste water remediation and plant immunity. *Journal of Cleaner Production, 318*, 128522.

Sangwan, S., Sharma, P., Wati, L., & Mehta, S. (2023). Chapter 4—Effect of chitosan nanoparticles on growth and physiology of crop plants. In A. Husen (Ed.), *Engineered nanomaterials for sustainable agricultural production, soil improvement and stress management* (pp. 99–123). Academic.

Satti, S. H., Raja, N. I., Ikram, M., Oraby, H. F., Mashwani, Z.-U.-R., Mohamed, A. H., et al. (2022). Plant-based titanium dioxide nanoparticles trigger biochemical and proteome modifications in Triticum aestivum L. under biotic stress of Puccinia striiformis. *Molecules, 27*, 4274.

Sen, M. (2020). Nanocomposite materials. In *Nanotechnology and the environment*. IntechOpen.
Shaghaleh, H., Alhaj Hamoud, Y., Xu, X., Wang, S., & Liu, H. (2022). A pH-responsive/sustained release nitrogen fertilizer hydrogel based on aminated cellulose nanofiber/cationic copolymer for application in irrigated neutral soils. *Journal of Cleaner Production, 368*, 133098.
Shahid, S. A., Zaman, M., & Heng, L. (2018). Soil salinity: Historical perspectives and a world overview of the problem. In M. Zaman, S. A. Shahid, & L. Heng (Eds.), *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques* (pp. 43–53). Springer International Publishing.
Shaikh, B. B. R., Toksha, B. G., Shirsath, S. E., Chatterjee, A., Tonde, S., & Chishty, S. Q. (2021). Microstructure, magnetic, and dielectric interplay in NiCuZn ferrite with rare earth doping for magneto-dielectric applications. *Journal of Magnetism and Magnetic Materials, 537*, 168229.
Sharifi, R. (2016). Effect of seed priming and foliar application with micronutrients on quality of forage corn (Zea mays). *Environmental and Experimental Biology, 14*, 151–156.
Sharma, G., Prajapati, D., Devi, K. A., Pal, A., & Saharan, V. (2022). Chapter 11—Chitosan nanomaterials for delivery of micronutrients in plants. In S. Kumar & S. V. Madihally (Eds.), *Role of chitosan and chitosan-based nanomaterials in plant sciences* (pp. 239–253). Academic.
Shebl, A., Hassan, A. A., Salama, D. M., Abd El-Aziz, M. E., & Abd Elwahed, M. S. A. (2020). Template-free microwave-assisted hydrothermal synthesis of manganese zinc ferrite as a nanofertilizer for squash plant (Cucurbita pepo L). *Heliyon, 6*, e03596.
Sheldon, A. R., Dalal, R. C., Kirchhof, G., Kopittke, P. M., & Menzies, N. W. (2017). The effect of salinity on plant-available water. *Plant and Soil, 418*, 477–491.
Sigmon, L. R., Adisa, I. O., Liu, B., Elmer, W. H., White, J. C., Dimkpa, C. O., & Fairbrother, D. H. (2021). Biodegradable polymer nanocomposites provide effective delivery and reduce phosphorus loss during plant growth. *ACS Agricultural Science & Technology, 1*, 529–539.
Song, U., & Kim, J. (2020). Zinc oxide nanoparticles: A potential micronutrient fertilizer for horticultural crops with little toxicity. *Horticulture, Environment, and Biotechnology, 61*, 625–631.
Soraki, R. K., Gerami, M., & Ramezani, M. (2021). Effect of graphene / metal nanocomposites on the key genes involved in rosmarinic acid biosynthesis pathway and its accumulation in Melissa officinalis. *BMC Plant Biology, 21*, 260.
Sturikova, H., Krystofova, O., Huska, D., & Adam, V. (2018). Zinc, zinc nanoparticles and plants. *Journal of Hazardous Materials, 349*, 101–110.
Szőllősi, R., Molnár, Á., Kondak, S., & Kolbert, Z. (2020). Dual effect of nanomaterials on germination and seedling growth: Stimulation vs. Phytotoxicity. *Plants, 9*, 1745.
Tighe-Neira, R., Carmora, E., Recio, G., Nunes-Nesi, A., Reyes-Dias, M., Alberdi, M., Rengel, Z., Inostrazo-Blancheteau, C. (2018). Metallic nanoparticles influence the structure and function of the photosynthetic apparatus in plants. *Plant Physiology and Biochemistry, 130*, 408–417.
Toksha, B. G., Shirsath, S. E., Patange, S. M., & Jadhav, K. M. (2008). Structural investigations and magnetic properties of cobalt ferrite nanoparticles prepared by sol–gel auto combustion method. *Solid State Communications, 147*, 479–483.
Toksha, B. G., Shirsath, S. E., Mane, M. L., & Jadhav, K. M. (2017). Auto-ignition synthesis of $CoFe_2O_4$ with Al^{3+} substitution for high frequency applications. *Ceramics International, 43*, 14347–14353.
Toksha, B., Sonawale, V. A. M., Vanarase, A., Bornare, D., Tonde, S., Hazra, C., et al. (2021). Nanofertilizers: A review on synthesis and impact of their use on crop yield and environment. *Environmental Technology & Innovation, 24*, 101986.
Tombuloglu, H., Slimani, Y., Tombuloglu, G., Alshammari, T., Almessiere, M., Korkmaz, A. D., et al. (2020). Engineered magnetic nanoparticles enhance chlorophyll content and growth of barley through the induction of photosystem genes. *Environmental Science and Pollution Research International, 27*, 34311–34321.
Tripathi, D. K., Singh, S., Singh, S., Mishra, S., Chauhan, D. K., & Dubey, N. K. (2015). Micronutrients and their diverse role in agricultural crops: Advances and future prospective. *Acta Physiologiae Plantarum, 37*, 139.

Umar, W., Czinkota, I., Gulyás, M., Aziz, T., & Hameed, M. K. (2022). Development and characterization of slow release N and Zn fertilizer by coating urea with Zn fortified nano-bentonite and ZnO NPs using various binders. *Environmental Technology & Innovation, 26*, 102250.

Verma, S. K., Das, A. K., Patel, M. K., Shah, A., Kumar, V., & Gantait, S. (2018). Engineered nanomaterials for plant growth and development: A perspective analysis. *Science of the Total Environment, 630*, 1413–1435.

Verma, S. K., Das, A. K., Gantait, S., Kumar, V., & Gurel, E. (2019). Applications of carbon nanomaterials in the plant system: A perspective view on the pros and cons. *Science of the Total Environment, 667*, 485–499.

Walker, S., Jaime, R., Kagot, V., & Probst, C. (2018). Comparative effects of hermetic and traditional storage devices on maize grain: Mycotoxin development, insect infestation and grain quality. *Journal of Stored Products Research, 77*, 34–44.

Wang, X., Cai, A., Wen, X., Jing, D., Qi, H., & Yuan, H. (2017). Graphene oxide-Fe3O4 nanocomposites as high-performance antifungal agents against Plasmopara viticola. *Science China Materials, 60*, 258–268.

Wang, R., Liu, L., Guo, Y., He, X., & Lu, Q. (2020). Effects of deterioration and mildewing on the quality of wheat seeds with different moisture contents during storage. *RSC Advances, 10*, 14581–14594.

Wawrzyniak, J., Waśkiewicz, A., & Ryniecki, A. (2018). Evaluation of critical points of mould growth and mycotoxin production in the stored barley ecosystem with a hazardous initial microbiological state of grain. *Journal of Stored Products Research, 77*, 166–176.

White, P. J., & Brown, P. H. (2010). Plant nutrition for sustainable development and global health | Annals of Botany | Oxford Academic. *Annals of Botany, 105*, 1073–1080.

Xu, Z., Jiang, X., Li, Y., Ma, X., Tang, Y., Li, H., et al. (2022). Antifungal activity of montmorillonite/peptide aptamer nanocomposite against Colletotrichum gloeosporioides on Stylosanthes. *International Journal of Biological Macromolecules, 217*, 282–290.

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

Zarinkoob, A., Esmaeilzadeh Bahabadi, S., Rahdar, A., Hasanein, P., & Sharifan, H. (2021). Ce-Mn ferrite nanocomposite promoted the photosynthesis, fortification of total yield, and elongation of wheat (Triticum aestivum L.). *Environmental Monitoring and Assessment, 193*, 800.

Zhang, D.-D., Hu, S., Wu, Q., Zhao, J.-F., Su, K.-R., Tan, L.-Q., & Zhou, X.-Q. (2022a). Construction of ZnO@mSiO2 antibacterial nanocomposite for inhibition of microorganisms during Zea mays storage and improving the germination. *LWT, 168*, 113907.

Zhang, H., Yuan, M., Tang, C., Wang, R., Cao, M., Chen, X., et al. (2022b). A novel nanocomposite that effectively prevents powdery mildew infection in wheat. *Journal of Plant Physiology, 279*, 153858.

Zhao, Y., Zhu, X., Chen, X., & Zhou, J.-M. (2022). From plant immunity to crop disease resistance. *Journal of Genetics and Genomics, 49*, 693–703.

Zhou, L., Zhao, P., Chi, Y., Wang, D., Wang, P., Liu, N., et al. (2017). Controlling the hydrolysis and loss of nitrogen fertilizer (urea) by using a nanocomposite favors plant growth. *ChemSusChem, 10*, 2068–2079.