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REVIEW ARTICLE

Nano-technological interventions in crop production—a review

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Abstract Agricultural industry is facing huge crisis due to fast changing climate, decreased soil fertility, macro and micronutrient insufficiency, misuse of chemical fertilizers and pesticides, and heavy metal presence in soil. With exponential increase in world's population, food consumption has increased significantly. Maintaining the production to consumption ratio is a significant challenge due to shortage caused by various issues faced by agricultural industry even with the improved agricultural practices. Recent scientific evidence suggests that nanotechnology can positively impact the agriculture sector by reducing the harmful effects of farming operations on human health and nature, as well as improving food productivity and security. Farmers are combining improved agricultural practices like usage of fertilizers, pesticides etc. with nano-based materials to improve the efficiency and productivity of crops. Nano technology is also playing a significant role improving animal health products, food packaging materials, and nanosensors for detecting pathogens, toxins, and heavy metals in soil among others. The nanobased materials have improved the productivity twice with half the resources being utilized. Nanoparticles that are currently in use include titanium dioxide, zinc oxide, silicon oxide, magnesium oxide, gold, and silver used for increasing soil fertility and plant growth. Crop growth, yield, and productivity are improved by controlled release nanofertilizers. In this review we elaborate on the recent developments in the agricultural sector by the usage of nanomaterial based composites which has significantly improved the agricultural sector especially how nanoparticles play an important role in plant growth and soil fertility, in controlling plant diseases by the use of nanopesticides, nanoinsecticides, nanofertilizers, Nanoherbicides, nanobionics, nanobiosensors. The review also highlights the mechanism of migration of nanoparticles in plants and most importantly the effects of nanoparticles in causing plant and soil toxicity.

Keywords Nanoparticles · Plant growth · Soil fertility · Plant diseases · Nanopesticides · Nanofertilizers · Soil toxicity

Introduction

Global warming, decreased growth, viable raw material use, plant diseases and environmental issues such as overflow of pesticides and fertilizer buildup has affected the crop productivity in agriculture sector. These issues are exacerbated by increasing food demand, which is expected to feed 6–9 billion people by 2050. New opportunities are emerging, such as the generation of electrical energy from agronomic waste, but feasible finances and supportive policy must support them. A fast expanding and hybrid agricultural system is currently present, and increasingly serious challenges need to be addressed by developing nations because agriculture is the nation's economic strength. Many significant challenges confront rising countries, like shortage of fertile land, loss of current agricultural lands due to competing economic growth activities, commodity dependency, scarcity, and malnourishment, all of which must be addressed over time. Rapid technological innovation over the last several decades has resulted in profound organizational changes in the agricultural sector. Nanotechnology and engineering are part of a broad and exciting scientific tool that will substantially affect every feature of the worldwide economy, industry, and public lives in the twenty-first century. The nanoscale sciences

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reveal the properties, techniques, and matter phenomena at the nanometer (1–100 nm) scale (Chen and Yada 2011).

Nanotechnology is considered as largest growing technology of the decade, with potential applications in agriculture. Nanotools such as nanofertilizer and nanopesticide have transformed traditional farming methods into precision farming. Various and nanoformulations of traditional agricultural inputs such as azadiractina, validamycin etc. have been transformed into nanopesticides and nanofertilizers (Konappa et al. 2021). The nanoforms have shown promising results on seed, plant development, and production at optimum concentrations. Similarly, nanopesticides had an affirmative impact on plant disease control (Chhipa and Joshi 2016).

Biological methods, can be used to generate nanomaterials, which have a great potential for creating eco-friendly nanomaterials (Sharma et al. 2019). Soil is fertile if it contains and can supply all essential plant nutrients needed for growing crop plants in adequate amounts. The quantity of these important plant nutrients should not be deficient or toxic. To be productive, the soil must be free of natural hazards such as floods and associated erosion. Soil fertility is the key to long-term agricultural success (Kumar 2021). Nanotechnology has improved human control of soil conditions through different applications such as nanosensors to measure soil conditions, the penetration of chemicals, ecological pollution, and safety assurance contributing to the sustainability of agronomy and the environment. Nanoscience have shown encouraging outcomes in terms of increasing food security, grade, product traceability, nutrition delivery, presentation of package, agriculture and food processing, and a superior sustainable farming (Dasgupta et al. 2017).

In this review, we focus on conventional methods for agriculture practices followed by farmers, the role of nanoparticles in improving crop productivity, plant growth, soil fertility, migration in plants, its capability to control plant diseases, and the toxic effects on soil and plants on agriculture field. New advancements in nano-based products over commercial chemicals examine appropriate agro based technologies to address the gaps and ensure long term helpful agricultural methods for global food safety and security. As a result, nanoparticles are developing as an innovative technology for agriculture. Exceptionally, they offer stress resistance, support plant growth, and disease control in crops. The review aims to briefly explain, use of nanotechnology in agriculture to understand the existing situation worldwide and serve as a foundation for suggestions and future schemes based on some of the most current scientific understanding.

Conventional methods of crop production

The continuous increase in the human population leads to a rise in crop production. The agricultural farms are losing soil fertility due to human and environmental activities. When plants lack micronutrients it results in an abnormal growth in plants. The leftover nutrients enter the aquatic system and cause eutrophication. Commercial fertilizers are essential for increasing crop yields, but ineffectiveness in fertilizer supervision can have significant financial and conservational effects. At least the majority of the nitrogen fertilizer given to farms is lost to abiotic factors and other processes, resulting in severe natural repercussions such as nitrate leaching into aquatic ecosystems and N-oxide emissions into the atmosphere. Phosphorus utilization efficiency is very low, which is a serious problem because phosphorus is a limited resource and overspills exacerbate eutrophication in aquatic environments. Inefficient fertilization has a significant economic impact that cannot be ignored (Mastronardi et al. 2015). Because 90% of pesticides applied to diseases and pests are squandered, traditional pesticide control methods have harmed the environment and agronomists' financial interests. Pesticide use that is indiscriminate promotes pesticide resistance, lowers soil biodiversity, and reduces N_2 fixation; it also contributes to pesticide bioaccumulation among others. Chemical formulations of fertilizers and pesticides have severely affected human wellbeing, and disrupted ecosystem sub—divisions through runoff and eutrophication. For sustainable agriculture, it is necessary to transform traditional farming operations into innovative farming practices by incorporating new technologies such as nanotechnology (Satpute et al. 2021).

Soil-microbe interactions determine the potentiality of soil agricultural productivity. While the relationship of plants and microbes is a significant element in determining ecosystem functioning, these plant–microbe interactions vary widely and are dependent on food availability (Singh et al. 2016). Plant growth-boosting microorganisms are primarily utilized to promote plant development through a diverse set of mechanisms for instance plant growth control and nutrient absorption (Kumar and Verma 2019). Microbial composts are like arbuscular mycorrhizal fungi etc. has significant impact on plant development (Pérez-Montaño et al. 2014). Table 1 depicts the conventional microbes which are helpful in soil fertility and plant growth. Efficacious microorganisms might enhance crop development and yield and expedite the disintegration of organic compounds in the soil (Hu et al. 2018).

Nanoparticles for improved crop production

Nanoparticles play an important role in the seed germination, photosynthesis, crop yield, helps in controlling disease and provide resistance in crops (Shang et al. 2019). Modern agricultural practices have focused on nanostructures as Nano fertilizers for overall growth dynamics, physiology

Table 1 Role of microorganisms in plant growth and soil fertility

Microorganisms	Role	References
Arbuscular mycorrhizae	Increases plant growth and crop yield	Kumar and Verma 2019)
Photosynthetic bacteria, lactic acid producing bacteria, yeasts, actinomycetes, and fermenting fungi like *Aspergillus,* and *Penicillium*	Promote growth and increase efficiency of degradation of organic materials	Hu et al. (2018)
Azotobacter, Azospirillum, phosphorus solubilizing bacteria (PSB), and Vesicular Arbuscular Mycorrhiza (VAM)	Enhanced accumulation of plant nutrients	López-Valdez et al. (2018)
Trichoderma harzianum	Improves soil fertility and enhances tomato productivity	Lin et al. (2020)
Plant growth promoting bacteria (PGPB)	Soil improvement	Majeed et al. (2018)
Potassium solubilizing bacteria (KSB)	Helps in promoting plant growth	Etesami et al. (2017)
Phosphorous and Phosphate Solubilizing Bacteria	Plant nutrition	Satyaprakash (2017)
Plant-growth-promoting rhizobacteria and rhizobium	Removing heavy metal from soil	Ju et al. (2019)
Chytridiomycota, Zygomycota, Glomeromycota, Ascomycota, and Basidiomycota	Improves in plant growth and soil health	Devi et al. (2020)
Plant growth-promoting (PGP) archaea and bacteria	Helps in solubilizing nutrients, producing growth modulators, carbon fixation, competitive eliminations of harmful microbes, and soil remediation	Ayangbenro and Olubuloko (2020)
Proteobacteria, Firmicutes, Acidobacteria	Improves in soil fertility	Das et al. (2017)
Rhizobacteria and Mycorrhizae Consortium	Enhances crop nutrition, productivity and fertility of the soil	Raklami et al. (2019)
Actinobacteria and Proteobacteria	Improves crop yields and soil fertility	Cesarano et al. (2017)
E. coli, Salmonella, and *Yersinia*	Improvement soil health and promoting crop yields	
Plant growth promoting rhizobacteria (PGPR)	Helps in crop improvement Improves nitrogen fixation	Nath Yadav et al. (2017), Di Benedetto et al. (2017)

and metabolite production responsible for vital functioning of the plants (Mittal et al. 2020). Several reports suggest the combination of metal nanoparticles like Fe, Zn, Cu, nano-N, nano-P, nano-K etc. with commercial fertilizers as foliar spray drastically improved plant growth, economic yield, NPK nutrient use efficiency (NUE) among other parameters (Rahman et al. 2021; Abd El-Azeim et al. 2020). The advance properties of Nano fertilizers like smaller particle size, larger surface area and more particle per volume is utilized by the chemical applicators improving release and penetration into plant system, leading to increase utilization, bioavailability, performance and effectiveness (Al-Juthery et al. 2021). In addition slow-release of nano-fertilizers are utilized to offset the wastage of inorganic fertilizer. As a result, plants would be able to absorb the bulk of their nutritional requirements without loss of essential nutrients. Amino acids and sugars like mannose are often utilized along with nano-fertilizers, as they aid in enhanced nutritional absorption. Furthermore, nano-composites increase nutrient solubility and diffusion in soils, enhancing plant uptake. (El-Saadony et al. 2021). Field studies on nutrient usage efficiency of engineered nano-fertilizers in rice showed much higher usage efficiency than traditional fertilizer application, resulting in higher crop yield (7.9 ton/ha) by only providing half the necessary nitrogen-nutrient value compared to traditional application (7.3 ton/ha)(Carmona et al. 2022). Similarly, usage of nano-N, nano-P and nano-K showed higher values of economic yield, NUE, harvest index, starch values compared to control treatments (Abd El-Azeim et al. 2020). In tomato plants, commercial fertilizers combined with nanoparticles total production, NUE and benefit cost ratio increased by 25% compared to commercial fertilizer treated plants (Rahman et al. 2021).

Role of nanoparticles in plant growth

It is critical to deliver nanoparticle-based agrochemicals to specific crops, which can be accomplished using nano-capsules that are highly steady and have decomposable configurations. The increasing usage of nanoparticles in agriculture increases the efficiency of chemical insecticides by strengthening targeted delivery, welfare, infection, and pesticide adherence, thus lowering plant protection costs (Kaushal 2018). Oxidized nanoparticles such as Ca, Mg, Zn oxides, and titanium dioxide nanomaterials have also been often advocated due to their superior catalytic, electrical, and light absorption properties. Polymeric shells, for example, have been proposed as a method to improve nanoparticle biocompatibility (Table 2). Nanostructures like silica nanoparticles have been produced from a porous channel with a highly functionalizable larger surface (Sanzari et al. 2019).

The plants absorb nanoparticles through the shoot and root entry which further penetrates the roots (Fig. 1). Nanoparticles can have both positive and negative effects on plants, primarily dictated by their physicochemical characteristics; size and concentration are the most common, with higher concentration having a negative influence and moderate concentration having a favorable one (Ruttkay-Nedecky et al. 2017).

After absorption of nutrients, nanofertilizers encapsulating nanosilica can create binary layers on bacterial and fungal cell wall, preventing infections and improving plant development under high temperature and humidity, and disease battle. SiO_2 nanoparticles can boost growth of seedling and root improvement; silicon-based fertilizers rise in plant resistance (Rastogi et al. 2019). Titanium dioxide or non-toxic titanium can be used as a fertilizer ingredient to improve food output. Zinc oxide nanoparticles increased *Cyamopsis tetragonoloba* plant biomass, shoot and root progression, root region, chlorophyll, protein synthesis, rhizosphere bacteriological population, acid phosphatase, alkaline phosphatase, and phytase activity in the cluster bean rhizosphere (Khati et al. 2018). *Pseudomonas fluorescens, Bacillus subtilis, Paenibacillus elgii, and Pseudomonas putida*

Table 2 Role of nanoparticles in plant growth

Nanoparticle	Application for plant growth	References
Carbon nanotubes	Separating water pollutants from soil, root elongation, plant growth, seedling growth	Kaushal (2018)
Graphene oxide	Plant germination	Sanzari et al. (2019)
Gold	Enhanced seed germination of *Arabidopsis thaliana*	Kaushal (2018)
Zinc oxide rods	Enhance broccoli plant	Kaushal (2018)
Silver	Enhances plant growth	Sadak (2019)
	Inhibition of harmful bacteria and promoting plant growth	Ibrahim et al. (2019)
	Modulation in plant growth	Khan and Bano (2016)
	Improved plant growth and salts accumulation in pearl millet	Imran Khan et al. (2021)
	Root length of maize, cabbage, and barley plants enhance the number of leaves, leaf area, and plant height in borage	Kaushal (2018)
Multi-walled carbon nanotubes	Kernel germination	Kaushal (2018)
Aluminium oxide	Increased average root lengths of plants	Farooqui et al. (2016)
Zinc oxide	Increases phosphorous supplementation in cotton plants	Venkatachalam et al. (2017)
	seedling emergence and germination in wheat	Singh et al. (2019)
Zinc and iron oxide	Improvement in plant growth	Rizwan et al. (2019)
Silicon	Plants more resistant to drought, high temperature	Rastogi et al. (2019)
Zinc sulphide	Increased root-shoot length, pigment content	Thapa et al. (2019)
Titanium oxide	Increased plant productivity and soil health	Chavan et al. (2020)
Copper	Enhanced plant growth and grain yield	Van Nguyen et al. (2021)
Iron oxide	Removal of heavy metals from contaminated soil	Zhou et al. (2021)

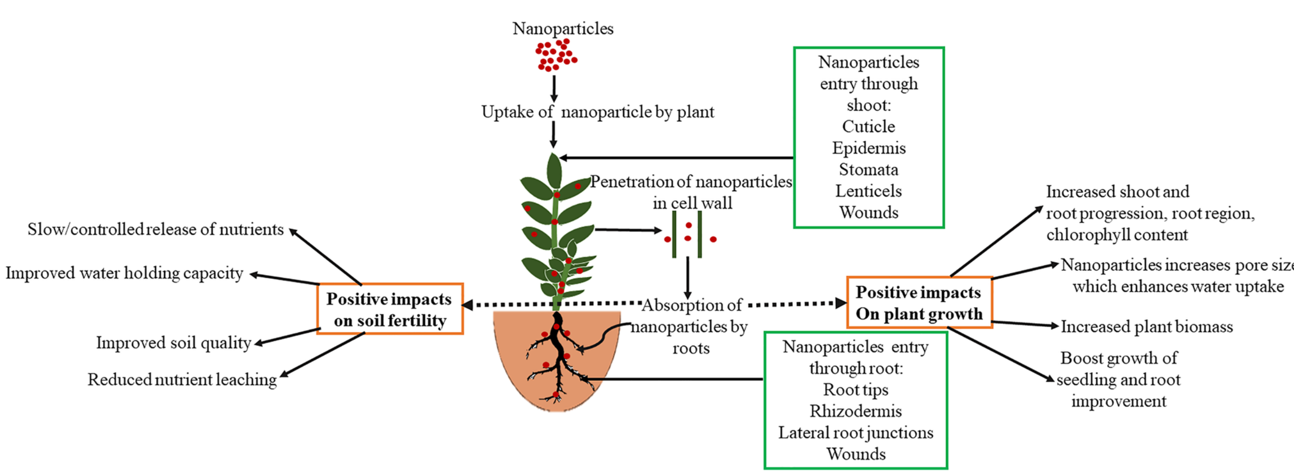

Fig. 1 Modes of nanoparticle uptake and positive impacts on plant growth and soil fertility

treated with gold, aluminum, and silver-coated nanoparticles increased plant growth, inhibiting the growth of harmful fungal parasites in the rhizosphere, making them as potential nano-biofertilizers (Duhan et al. 2017; Fig. 1). Foliar application of bio-fertilizer has also led to remarkable crop yields (Shang et al. 2019). Nanotechnology has played an essential role in agriculture and in enhancing the standard of life.

Role of nanoparticles in soil fertility

There are different agro-economic practices for soil fertility through the help of microorganisms. Environmental friendly, nano-fertilizer promotes soil accumulation, moisture withholding, and carbon building. It has no health risk and is suitable for agricultural crops, including cereals, vegetables, and horticulture. In contrast to mineral salt, mesoporous aluminosilicate-based nanoparticles offer a high potential for efficient and controlled macroscale and micronutrients release in soil, resulting in better plant growth and production (Zulfiqar et al. 2019). Compared to zinc sulphate, the use of a nano-sized $MnCO_3$ hollow core–shell system led to gradual and consistent release of zinc in rice under aerobic and submerged conditions. The use of silicon oxide-titanium nanomaterials in soybean enhanced the activity of nitrate reductase, which improved nutrient absorption.

Similarly, when compared to chelated iron, the application of Fe_2O_3 nanoparticles resulted in better nutrient uptake and, as a result, improved growth and productivity of peanuts (Ditta et al. 2020). Metallic nanoparticles are bioavailable to plants and have the potential to have a significant impact on food crops. Metals from the soil were bioacculmulated by the soybean plants, and in the case of zinc oxide nanoparticles, substantial quantities of metal were translocated into the leaves and beans (Fig. 1). Although zinc oxide nanoparticles had no effect on above ground biomass yield, plants grown with a high zinc oxide nanoparticle content produced more below ground biomass (Priester et al. 2012; Table 3).

Nanoparticles in controlling plant diseases

The inoculation of helpful bacteria onto seeds promotes plant growth. Nano-agrochemicals are essentially nano-reformulations of chemical pesticides and fungicides proven to provide long-term plant protection while reducing chemical use. Plant infections caused by pathogens, results in reduced output, product value, and shelf life, resulting in economic loss.

Nanoparticles incorporated with insecticides, herbicides and pesticides can protect plants (Hazarika et al. 2022; Fig. 2). Carbon nanoparticles, silver nanoparticles, silica nanoparticles, and alumino-silicate nanoparticles are most common nanoparticles used to control plant diseases. Silver stimulates plant growth. Nano Silver has been demonstrated to have powerful bactericidal and broad-spectrum antibacterial effects. Silicon has been shown to be absorbed by plants in order to decrease disease and stress tolerance. Alumino-Silicate nanotubes are also being developed for spraying on plant surfaces, and they are easily taken up in insect hairs.

Table 3 Role of nanoparticles in soil fertility

Nanoparticle	Application for soil fertility	References
Zinc oxide	Grew wheat in acidic and alkaline soils	Servin et al. (2015)
Silver	Movement in soil with the clay content	Servin et al. (2015)
Cerium oxide	Retention of nutrients in the soil	Servin and White (2016)
Titanium oxide	RUBISCO activity and enhanced photosynthesis	Servin et al. (2015)
Silver	Enhances soil fertility	Ameen et al. (2021)
Silver	Deteriorate mutual interaction between plants and fungi and negatively influence the rhizospheric soil	Cao et al. (2017)
Selenium	Enhanced soil fertility by promoting poly-microbial biofilms	Gudkov et al. (2020)
Zero-valent iron	Helps in removing hexavalent chromium metal from contaminated land	Su et al. 2016
Iron oxide	Degradation of chlorpyrifos	Das et al. (2020)
Copper oxide	Helps in nitrogen fixation in soil	Guan et al. (2020)
Silicon oxide	Improved seed germination	Fayiga and Saha (2017)
Silicon and Silicon-Based Nanoparticles	Improvement in rhizospheric microbiome	Rajput et al. (2021b)
Silver	Enhancement in composition of microbial community	Montes de Oca-Vásquez et al. (2020)
Iron Oxide	Influences soil properties	Claudio et al. (2017)
Zinc oxide	Influencing soil properties (control moisture distribution, evaporation, water permeation processes after irrigation)	Sheteiwy et al. (2021)
Cerium oxide	Influences Soil organic matter	Majumdar et al. (2016)
Metal-based nanoparticles	Influence Soil Properties	Dimkpa (2018)

Table 4 Nanoparticles helps in controlling plant diseases

Nanoparticles	Diseases	References
Nanosilver	Antifungal activity on pathogenic fungi, *Bipolaris sorokiniana*, and *Magnaporthe grisea*	Gour et al. (2019)
Nanocopper	Bacterial tomato spot	Gour et al. (2019)
Magnesium oxide	Antifungal action on *Alternaria alternate, Fusarium oxysporum, Rhizopus stolonifer,* and *Mucor plumbeus*	Gour et al. (2019)
Zinc oxide	Antifungal activity against Pathogenic fungi (Alternaria alternate, *Fusarium oxysporum, Rhizopus stolonifer,* and *Mucor plumbeus)*	Gour et al. (2019)
Silver nanoparticle	Antifunal activity against *Sclerotinia sclerotiorum*	Kumar et al. (2019); Ali et al. (2020)
	Helps in eliminating Phytopathogenic fungi	
	Antibacterial activity on *Pseudomonas poae strain*	
Palladium and platinum nanoparticles	Inhibition of toxic tellurite	Ali et al. (2020)
Copper oxide	Antifungal agent-*Poria hypolateritia*	Ali et al. (2020)
Nickel	Inhibition of *Colletotrichum musae* in Banana	Ali et al. (2020)
Titanium oxide and silver nanoparticles	Leaf spot and blight symptoms, which *Alternaria* causes, alternate on potato and tomato	El-Gazzar and Ismail (2020)
Manganese and titanium oxide	Enhance growth of tomatoes and eggplants in disease infested soil	Servin et al. (2015)
Copper oxide, Manganese oxide, titanium oxide and Zinc oxide	Protects watermelon in *Fusarium* wilt infections	Elmer et al. (2018)
Encapsulated nanosilver	Removes unwanted microbes from soil	Tripathi et al. (2018)
Nano-forms of carbon, silver, silica and alumina silicates	Control of crops diseases	Tripathi et al. (2018)
Silver	Early blight disease in tomatoes	Kumari et al. (2017)
	Pythium aphanidermatum infecting tomato	Elshahawy et al. (2018)
Copper	Insect-pests and pathogenic microbes	Rai et al. (2018)

Insects aggressively groom and devour pesticide-filled nanotubes (Kumar et al. 2019).

Cerium oxide nanoparticles, have been found to accumulate in the roots of exposed soybeans before being translocated to edible tissue. Titanium oxide nanoparticles in agriculture, including disease protection, are based on photocatalytic surface properties (Rastogi et al. 2017). The foliar application of copper oxide nanoparticle on *Phytophthora infestans* on tomato plants showed greater pathogen safety (73.5%) than bulk amendment (57.8%) (Servin et al. 2015). Table 4 depicts the nanoparticles which help in controlling plant diseases.

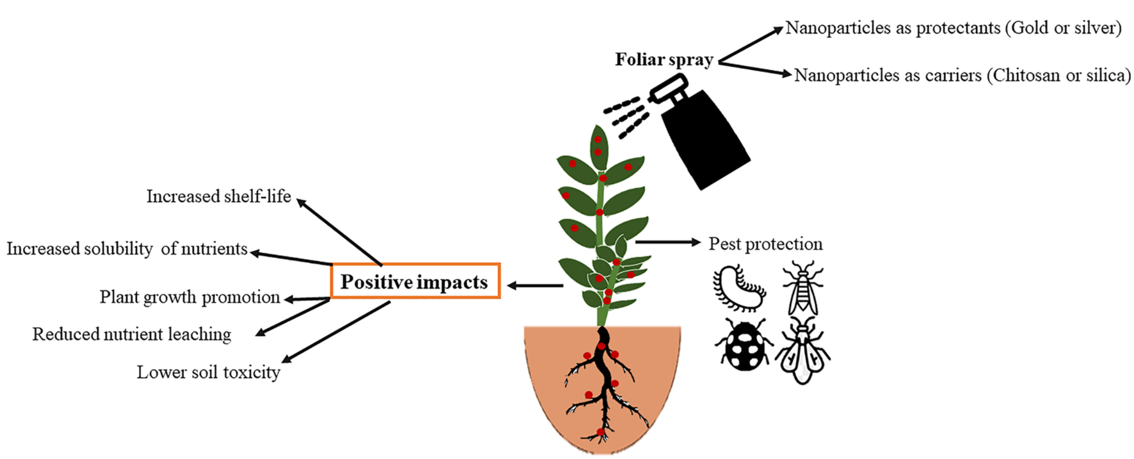

Fig. 2 Impact of nanoparticles in controlling plant diseases

Nanoparticles have also been involved in the detecting and battling against the plant pathogens and have played an important role in plant disease management. Nanoparticles like nano sized silver, nano copper etc. have shown antimicrobial property, delivery of the chemical to targeted site, improve the efficiency of the used chemical and controlling bacterial, fungal and other plant diseases (Vigneshwaran et al. 2007). Nanoparticle permeation into cells can result in attaching to cellular components, causing DNA and/or mitochondrial damage and protein inactivation, which has been considered as another important route of antimicrobial action. This action suggests nanoparticles to have many modes of action, which may make it difficult for bacteria to develop resistance, resulting in greater effectiveness (Fu et al. 2020). However, the precise mechanism by which nanomaterials exert their cytotoxic effects on phytopathogens at the molecular level is yet to be understood. During anti-fungal action, spores get attached or adhere onto carbon nanoparticles, resulting in direct spore-carbon nanoparticles interaction during incubation leading to spore water channel obstruction and spore plasmolysis as part of their antifungal action (Wang et al. 2014). The cell wall of fungus comprises of chitin, lipids, phospholipids, and polysaccharides, with mannoproteins. Internalization of nanomaterials happens via direct uptake of nanomaterials in the cell wall, specialized receptor-mediated binding followed by nanomaterial internalisation via ion carrier proteins (Alghuthaymi et al. 2021, Fig. 3).

Nano pesticides

The prevalence of insect pests in agricultural areas and their products are well-known, control of pathogens and pests by conventional agricultural production systems has led to increased pathogen and pest resistance, bioaccumulation of pesticides, reduction in nitrogen fixation and soil biodiversity. These environmental problems can be overcome by smart delivery systems, by the use of nanocarriers which are designed for enhanced efficiency, smart and targeted delivery, perform only on demand, suggesting significant role of nanoparticles in insect pests and host–pathogen management. Various studies have suggested nanopesticides have a wider success against various plant diseases. These nano based agrochemicals have shown potency against both bacterial and fungal pathogens (Pandey et al. 2018). Microencapsulation-like nanoencapsulation is employed to improve the superiority of intended chemical to target biological processes. Chemical firms have lately begun publicly promoting sale of nanoscale pesticides as "microencapsulated insecticides." Syngenta (Switzerland) products, such as Karate ZEON, Subdue MAXX, Ospray's Chyella, Penncap-M, and BASF's microencapsulated insecticides, may be nanoscale-fighting ready

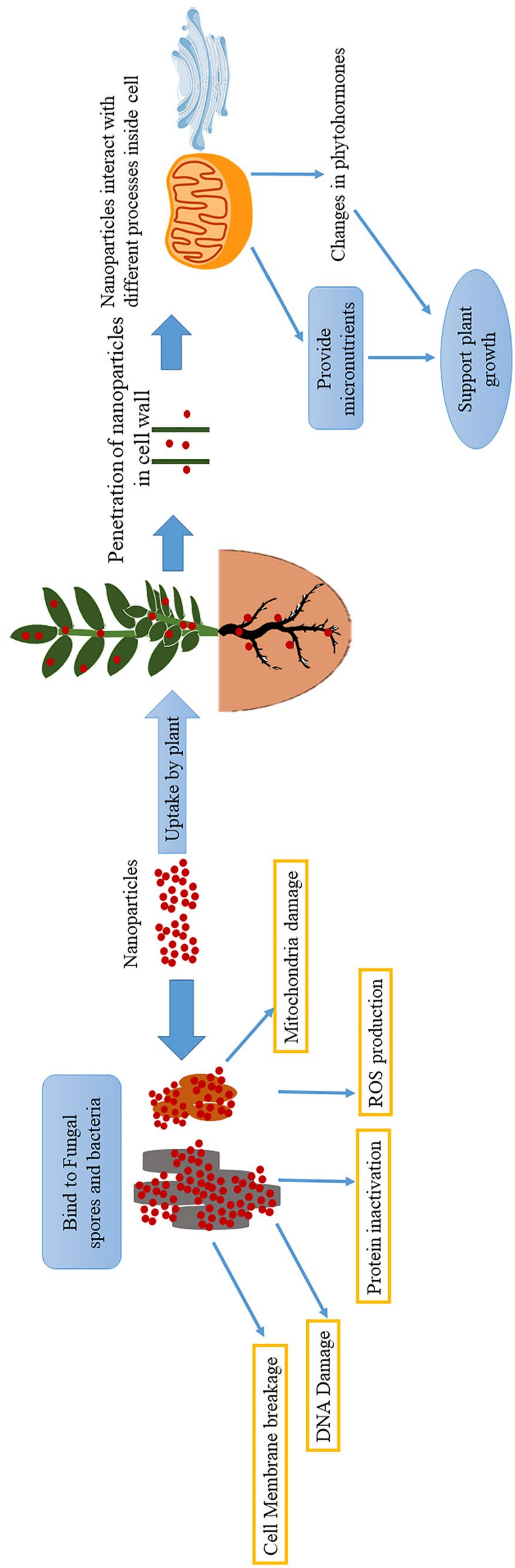

Fig. 3 Mechanisms of nanoparticles in promoting plant growth and controlling plant diseases

(Prasad et al. 2017). Copper-based nanopesticides have been found to be detrimental on spinach plants, altering metabolic profiles and decreasing antioxidant molecules including ascorbic acid, alfa-tocopherol, threonic acid, 4-hydroxybutyric acid, ferulic acid, and total phenolic components by 29–85%. (Paramo et al. 2020). Similarly, polymer based nanoformulations have enhanced the rate of sorption and photodegradation of half-life pesticide active ingredient in water and reduced the persistence of these in soil and water (Kah et al. 2018).

Nano insecticides

Synthetic pesticides have been an important tool to combat vectors of various diseases of plants. However these insecticides have impacted negatively by affecting non-targeted organisms and ecosystem. In addition to this it may lead to bioaccumulation posing serious threat both flora and fauna. Various nanoparticles like Ag, silica, ZnO, CuO, etc. have been utilized to overcome this issue (Deka et al. 2021) and have shown insecticidal properties. Pesticide delivery system (PDS) have been developed for optimal biological efficacy by delivering active compound to the specific target with specific concentration and time using nanoparticles. This not only targets the specific organisms but minimize the adverse effects in non-targeted insects. Nanoparticles as nanocarriers can be used to attach the molecules of insecticides. Polymer nanoparticles as nanocarriers like PEG (Polyethylene glycol) polymer nanoformulation based pesticides demonstrated significant slow liberation of active ingredient in comparison to chemical pesticides and better efficiency against nematodes (*Meloidogyne incognita*) and beetles (*Callosobruchus maculatus*)(Loha et al. 2012). Inorganic nanoparticles like Silica nanoparticles have been used for effective delivery of insecticides. Higher efficiency and slow release of chlorfenapyr was seen in pesticide formulations based on Silica nanoparticles (Mingming et al 2013). Silica nanoparticles also showed significant direct or indirect effects to kill or repel insect pests like *Aphis craccivora, Chrysoperla carnea,* etc. (Thabet et al. 2021). Larval mortality was observed in *Tenebrio molitor* and *Tinea pellionella* (Rankic et al. 2021) treated with nano-sized silver particles (Table 4).

Nanofertilizers

Nanofertilizers magnify the nutrient supervision, strengthen the soil for enhanced yield and improve the crop qualitatively and quantitatively. They improve the efficacy by controlled uptake of nutrients based on the need of the plants and prevents the misuse of fertilizers making it cost effective and preventing environmental damage (Akhtar et al. 2022). Properties like higher surface area, high solubility, small particle size, encapsulation, easy penetration and modulated liberation of fertilizers and effective span of nutrient release makes Nano fertilizer superior over conventional ones. Furthermore, multiple studies have demonstrated that the larger specific surface area and nanoparticle density confer strong reactivity on nanohybrids. The use of nanofertilizers has considerable potential for enhancing fertilizer uptake and agricultural production. Incorporating N, P, and K onto chitosan nanoparticles enhances N, P, and K uptake in cultured coffee plants by 17.04%, 16.31%, and 67.50%, respectively, compared to untreated plants (Liu et al. 2021).

Different types of nanoparticles have been reported which have been utilized as nanofertilizers like Nitrogen based nanofertilizer, Phosphate based nanofertilzers, Iron based nanofertilizers, etc. (Malik and Kumar 2014), even polymeric as dendrimers serving nanocarriers (Paramo et al. 2020) and core–shell quantum dots (QDs), gold nanorods, and core–shell QDs.

Due to the several desirable properties of nanofertilzers especially targeted and timely release it has proven to be of great importance in modern agriculture. These nano particles are usually delivered in to the usually by *in vitro* (Aeroponics and Hydroponics) or *in vivo* (soil and foliar application) methods. Once delivered the uptake of nanoparticle is based on the size, chemical composition, and physiology of the plant.

Nanoherbicides

Continuous use of herbicides have led to the development of herbicide resistant weeds. In spite of the resistant management practices like Integrated weed management, overuse of herbicide can lead to environmental damage and these practices may become obsolete. Nano structured herbicides could prove to be an alternative for reducing the herbicide consumption and improve the efficiency, enhance the solubility, reduce the toxicity rate and increase productivity rate. Nanoherbicides through controlled release via. encapsulation enters the root system and stops the glycolysis in plant root system creating starvation in weeds, ultimately killing it. Thus these nanoparticles can overcome the issues caused by herbicide resistant plants. Polymeric nanoparticles which are biodegradable are most commonly used for herbicide delivery. Atrazine herbicide encapsulated with Poly(epsilon caprolactone) enhanced bioavailability and herbicidal activity compared to free Atrazine (Pereira et al. 2014). Triazine herbicide encapsulated with polymeric nanoparticles showed better efficiency and less genotoxicity in experimental plants.

Nanobionics

During photosynthesis plants transform light energy into chemical energy for carbon based fuel and food supply.

Based on their intrinsic light intensity ability, nanoparticles have the potential to impede and affect photosynthetic efficiency, photochemical fluorescence, and quantum yield in plants. Single wall nanotube chloroplast assembles have shown higher rate of electron transport chain in vivo. Enhanced carbon fixation by increased absorption of light energy can be achieved by plasma resonance of metal nanoparticles (Giraldo et al. 2014). Titanium oxide accelerates the transfer of electrons, photolysis of water, and oxygen generation by promoting the conversion of light energy to electron energy. Treatment, on the other hand, lowered Photosystem I activity, with the enormous impact reported at a concentration of 5 μM anatase Titanium oxide nanoparticles (Su et al. 2007). Similar investigations in *Arabidopsis thaliana* revealed that the concentrations of light-harvesting complex II were 3.83 times higher in plants treated with titanium oxide nanoparticles than in control plants. (Kataria et al. 2019). It is also reported to enhance the photosynthetic carbon assimilation by activating RUBISCO (Anjali et al. 2012).

Compared to NaCl-alone treated plants, the treatment with ZnO nanoparticles in the presence/absence of NaCl significantly improved the performance of net photosynthetic rate, carbon dioxide concentration, stomatal conductance, internal transpiration rate, and chlorophyll content. This improvement was most remarkable in plants exposed to 50 mg/L of zinc oxide nanoparticles. Nanoparticles improved photosynthesis and associated properties by hastening water splitting and electron exchange via redox processes. The use of nanoparticles boosted the action of ribulose-1, 5-bisphosphate carboxylase/oxygenase, which was directly related to increased photosynthesis activity (Faizan et al. 2021). Nano-phosphorous fertilizer increased physiological phosphorus efficiency in both shoots and roots, resulting in increased biomass accumulation in both organs. The photosynthetic rate was shown to be favorably linked with phosphorus concentration in shoots and phosphorus accumulation in shoots and roots. In addition, nano-phosphorous improved the efficiency of immediate water utilization in rice crops. (Miranda-Villagómez et al. 2019).

Nanobiosensors

Many benefits of nanoscale materials' physical–chemical characteristics can also be used in the creation of biosensors. According to Sagadevan and Periasamy (2014), using nanomaterials and new signal transduction techniques can improve the sensitivity and performance of biosensors. Because of the high demand for sensitive, fast, and cost-effective nano biosensors systems in critical areas of anthropogenic activity. Biosensor systems have better specificity and sensitivity than traditional techniques because they contain a baroreceptor (a natural element) and a transducer interacting with a target molecule to create a signal. Bio receptors such as enzymes, dendrimers, thin films, and others have recently been created and put to use in a wide variety of applications. Biosensors are analytical devices that take a biological reaction and turn it into an electrical signal. It focuses on biological components, including antibodies, enzymes, proteins, nucleic acids, and constituents (Prasad et al. 2017). Various nanomaterials like gold, silver, quantum dots etc. have been utilized for the development of Nanosensors. Biosensors can be utilized for increasing the sustainable agricultural productivity as these can be used for sensing residual chemicals such as fertilizers and pesticides, monitoring of pathogens and their toxins and detection of heavy metals in the agricultural field (Kuswandi 2016).

Migration of nanomaterials in plants

Nanoparticles containing crucial metals are reflected in fertilizer formulations to improve plant nourishment in soils with less metal bioavailability. The nanomaterials are given to plant as foliar delivery, manual injection, or adsorption by plants are few methods for introducing nanoparticles to plants in the form of nano-fertilizers and nano-pesticides or insecticides (Shang et al. 2019). The nanoparticles enter through stomata, wounded tissue, or cuticle and interact with soil and soil microorganisms (Fig. 1). Further, it gets translocated in the plant body using apoplastic and symplastic pathways, which helps in plant growth and development (Mastronardi et al. 2015). They increase the efficiency with which water and necessary calcium and iron nutrients are absorbed, potentially improving seed germination and plant evolution and growth. It was proven in the that industrialized-grade multi-walled carbon nanotubes increased wheat germination and root elongation. As a result of oxidative stress, foliar treatment of aluminium oxide to wheat seedlings reduced root length and enhanced the activity of superoxide dismutase and catalase enzymes. Studies also discovered that a lower quantity of zinc oxide nanoparticles improved wheat seedling growth (Jsarotia et al. 2018). Nanofertilizers can improve plant nutrient uptake through these pores, or the procedure can enable complexation with molecular transporters or root exudates by creating new pores or employing endocytosis or ion channels (Aamir Iqbal 2020). Furthermore, many studies have evidently and unambiguously witnessed that the reduction in the size of nanomaterials facilitates the rise of particle surface mass ratio, as a result of which a large amount of nutrient ions are adsorbed desorbed gradually for an extended time. Fertilizer nanoformulations guarantee balanced nutrition of crops during the developmental cycle, ultimately improving agricultural production.

Current challenges and issues

Nanoparticles, as we know, both have benefits and drawbacks on plants and soil, impacting human health. Nanoparticles have favorable impacts on plant biomass; nevertheless, the negative effects of nanomaterials on plants would be thoroughly examined, and any negative consequences should not be overlooked. Despite tremendous progress in finding potential uses for nanotechnology in agriculture, several challenges must be overcome before this technology can substantially impact the sector. Major areas that needs additional consideration are: (i) development of specific hybrid carriers for delivering active agents such as nutrients, pesticides, and fertilizers in order to enhance their efficiency while adhering to green chemistry and environmental sustainability principles; (ii) the design of processes that are easily scalable to the industrial level; and (iii) the comparison of nutrient, pesticide, and fertilizer delivery systems. A step forward in the regulation of nanomaterials usage. Concerning nanopesticides exploitation development (like atrazine), it serves as a valuable case study to determine the most important characteristics needed to forecast how nanomaterials would behave in the environment. In order to understand nanomaterial dynamics in the environment, their interactions with target and non-target species, or the emergence of synergistic effects, currently existing techniques are insufficient. These methodological advancements enable the evaluation of the new nanomaterials' life cycle (Fraceto et al. 2016).

Toxicty associated with nanoparticles is however not very well documented. General toxicity of these nanomaterial's are seen especially associated with genotoxicity, cell membrane disruption, release of toxic compounds etc. General toxicity of nanomaterials is significantly associated with genotoxicity, cell membrane disruption, the release of toxic compounds etc. However, in nano-enabled particles, concentrations play a significant positive and negative roles. Higher concentration can significantly affect the physiological functioning of the plant. The ongoing use of nanoparticle-incorporated particles, especially in agriculture, may raise their presence in soil and crops (Rajput et al. 2021a), leading to soil toxicity and subsequent effects on plants. The larger the size of nanoparticles, the more harmful they are in nature. It has also been found that crystal shape effects nano-toxicity. For example, anatase, brookite, and rutile are three mineral ores of titanium oxide. Anatase which is most physiologically active among the three enzymes, causing cell death and membrane rupture (Singh et al. 2021).

Nanotechnology is emerging as unique technologies for food preservation, shelf life enhancement, and food security. Tailored nanoparticles of various sizes and shapes offer tremendous opportunities for use in the production, packing, handling, and preservation of quality products due to their specific physicochemical characteristics (Hossain et al. 2021). Integrating nanocomposites in carrageenans such as TiO_2, SiO_2, nano clay, and Copper sulfide to develop unique packaging materials with improved mechanical and antibacterial properties as well as water content and stable chemical properties can generate safe and nutritious foods. The use of carrageenan-based bio-nanomaterials as food packaging elements has yielded encouraging results in terms of boosting storage life and food quality by inhibiting microbiological development (Aga et al. 2021). Effectively incorporated CNPs in nanocomposites designed for food packaging can provide desirable structural and barrier qualities for applications (Garavand et al. 2022).

Plant toxicity

Nanoparticles can directly cause alterations in the plant membrane and defense mechanisms and indirectly can cause clogging effects and reactive oxygen species production (Navarro et al. 2008). Another concern with nanomaterial usage is the possibility for nanoparticle bioaccumulation within crops and trophic level transfer (Servin et al. 2015). Copper oxide nanoparticles can obstruct the progression of seeds and pollen germination in various *Arabidopsis thaliana* ecotypes. The harmful expression of zinc nanoparticles on plant biomass is fundamentally related to nanoparticle absorption on the root surface. Silver nanoparticles have been shown to harm plant biomass in wheat, where roots developed slowly and frequently branch. Antimicrobial agents containing silver nanoparticles are widely used. Their widespread use will inevitably result in nanoparticle buildup in the environment and, consequently, in plants. Nanoparticles at low absorptions can lead to growth in Chinese cabbage, while high concentrations inhibit growth (Guerriero and Cai 2018; Costa et al. 2020). There are five types of nanoparticles that have been proven to be harmful to seed germination and root growth in six advanced plant species, including radish, rape, ryegrass, lettuce, maize, and cucumber (Ahmad et al. 2022). The hindrance happened during the seed breeding phase rather than the seed soaking stage, and it was discovered that inhibition occurred when soybean plants were grown in soil supplemented with nanocerium oxide. Several research on the toxicity of nanoparticles on various plant species, including radish, corn, lettuce etc. have been conducted (Singh and Prasad 2017). The harmful effects of cadmium pollution on barley plants may be mitigated by rhizobacteria due to the bacteria's ability to bind cadmium ions from the soil, reducing the accessibility of cadmium in the soil. *Azospirullum brasilense* can mitigate the harmful effects of saline conditions on jojoba rooting. The bacteria reduced the effect of salinity on the plant's rooting ability and suggested that *A. brasilense* has a greater tolerance to salt stress. Salicylic acid inhibited the development of root hair cells by reducing some phenotypic effects and post-transcriptional processes linked with nanoparticles. Nanoparticles' negative effects are strongly connected to hormone levels, and adequate amounts of particular hormones can possibly reduce nanoparticle adverse effects. (Guerriero and Cai 2018). In certain cases toxicity depends on the release of ions eg. zinc and copper oxide nanoparticles and in some it depends on the increase of concentration above a certain level eg. Magnesium, Tungsten, Aluminum, Silicon oxide etc. (Aruoja et al. 2015).

Soil toxicity

The most severe problems in modern agriculture are changes in climatic conditions, natural wealth sustainability, environmental factors, suburbanization, pesticide deposition, and overuse of fertilizers (Ekinci et al. 2014). Microbial biomass is a significant indication of soil contamination. Various concentrations of silver nanoparticles reduced microbial biomass in a dose-dependent fashion. Soil contamination with iron oxide magnetic nanoparticles, on the other hand, had no influence on microbial biomass or bacterial abundance. Likewise, no substantial influence of titanium oxides on bacterial abundances was identified in the six soils studied. Titanium oxide and zinc oxide nanoparticles both reduced the amount of soil DNA that could be extracted (Simonin and Richaume 2015). The effects of silver nanoparticles on soil microbial communities may have been underestimated, and they are not well replicated when new silver nanoparticles are added to soils. While the concentrations employed are worst-case situations, the relative toxicities of processed and fresh materials should not be overlooked (Forstner et al. 2020).

Metal oxide nanoparticles had previously been demonstrated to accelerate the oxidation of the organic contaminants in colloidal solution, and they were thus predicted to affect changes in organic material in soil, particularly when an oxidant was added. The nanoparticles had no effect on the overall quantity of organic matter present in the soil. The presence of rhamnolipid (RL)-stabilized nanoscale zero-valent iron altered the bacterial population and boosted the relative number of Fe(III)-reducing bacteria, perhaps redistributing iron coupled cadmium into a more stable iron mineral component. Organic carbon concentration eventually declined and became stable, possibly due to Rhamnolipid (RL)-stabilized nanoscale zero-valent iron stimulating organic carbon bioavailability by modifying the bacterial community makeup (Xue et al. 2018).

Titanium oxide and copper oxide nanoparticles reduced soil microbial biomass and enzymatic activity in flooded paddy soil, affecting their community structures. A high quantity of iron oxide nanoparticles dramatically reduced the bacterial content of the soil. Nanoparticles of zinc oxide and cerium oxide reduced the plate counts of *Azotobacter*, P-solubilizing, and K-solubilizing bacteria and inhibited enzymatic activity. Copper ions produced by copper oxide nanoparticles were a primary source of mortality in both pathogenic and nonpathogenic bacteria (Rajput et al. 2018). Clays are considered to adsorb zinc ions via ion exchange and specific adsorption, the quantity of clay in calcareous soil was more than in acidic soil, which increased zinc holding capacity in the soil and hence lowered zinc availability to microorganisms. The quantity of organic matter in the soil has also been connected to zinc availability. The impacts of nanomaterials are heavily impacted by the variations in forms that occur in nature. Sewage sludge, for example, interacts with silver nanoparticles, with absorption rates with an efficiency greater than 90% for uncoated molecules than functionalized particles. Biofilm networks and unmodified societies have also arose as one of the expected concerns. For example, exopolysaccharides along with humic acids has capability to protect microorganisms and lower the toxic nature of silver nanomaterials (Javed et al. 2019).

Conclusion and outlook

Almost every aspect of agricultural science and crop research has been accelerated by nanotechnology. It is well agreed that the practice of nanomaterials in the scientific community and agricultural fields provides numerous advantages over traditional methods. Nanotechnology-based biofertilizers are highly beneficial to plant development and growth. Nanopesticides and nanoinsecticides are more effective against disease and damaging insects than chemical formulations. With the help of nanotechnology, effective delivery, specific time of release and concentration of active ingredient of various fertilizers and pesticides can be monitored hence avoiding bioaccumulation in soil and ecosystem. However concerns have been raised about the unrestrained and unregulated accretion of nanomaterials in soil. Toxicity of nanomaterials has been known since the late 1980s. The use of encapsulated metal nanofertilizers and nanopesticides in agriculture has proved their promising method. Nano fertilizers enhance crop development to the optimum applied doses, but they also have a suppressive effect on crops if the concentration is higher than the optimal levels, resulting in decreased crop growth and yield. Bio efficacy and toxicity to non-target organisms over long period of time also needs to be assessed. Since nanotechnology in agriculture must avoid biotechnology problems, it might take many decades to transition from the laboratory to the field. For this to happen, policymakers and scientific administrators need to have a clear grasp of the issues and have realistic expectations of how the profession will develop.

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