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Review article

# Employment of nanoparticles for improvement of plant growth and development

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**Abstract**

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Nanotechnology, with its research and results, has become one of the essential fields among scientific disciplines. Nanotechnology is used in many areas of science such as physics, chemistry, pharmacology, materials science, medicine and agriculture. The use of nanotechnology could provide breakthroughs that would revolutionise many scientific studies. The role of nanoparticles in plant nutrition under soil pollution represents a comprehensive overview of nanotechnology in agriculture related to the importance, recycling, and transformation of nanoparticles. Nanomaterials are used in plant protection, nutrition, and the management of agricultural practices. The new challenges nanotechnology faces today include using biological or green synthesis methods to produce nanoparticles and offset the toxicity of conventionally integrated nanoparticles. The efficiency of nanoparticle uptake and the effects of nanoparticles on growth and metabolic functions differ between plant species. The concentration of nanoparticles affects processes such as germination and plant growth and development. The agriculture sector has also profited from various nanotechnology-based products such as nanofertilisers, nanopesticides, nanogrowth promoters, and many more for sustainable agriculture and crop improvement.

**Keywords:** crops, nanocomposites, nanomaterials, nanopesticides, yield.

**Abbreviations:** Nanoparticles (NPs), Silver nanoparticles (AgNPs), Zinc nanoparticles (ZnNPs), Quantum dots (QDs), Titanium dioxide nanoparticles ($TiO_2$), Carbon nanotubes (CNTs), Silicon nanoparticles (SiNPs), biochar-based nanocomposites (BNCs), Nanomaterials (NMs)

## INTRODUCTION

The use of nanotechnology is increasing in almost every dimension of the plant, animal worlds, and among humans. The global market for nanomaterials may reach up to USD 100 billion by 2025, indicating a wider use of nanotechnology in every application area (Allan et al., 2021). Nanoparticles are increasingly used to enhance crop productivity, abiotic and biotic stress tolerance in plants, nanofertilizers, biosensors, cancer therapy, nanomedicines, cosmetics, electronics, and waste treatment. Nanoparticles affect plants at morphological, anatomical, biochemical, and molecular levels. (Siddiqui et al., 2022).

Agriculture is the most fundamental and stable sector supporting industrial growth and the economy, as it produces raw materials for the food and feed industries. Limitations in natural resources (productive land and water) and the increasing growth of the world population make researchers think about the development of agriculture economically, ecologically, and efficiently. Developing a sustainable agricultural sector is vital to eradicate hunger and poverty in our society (Manjunatha et al., 2016). Nanotechnology develops particles and molecular structures with dimensions in the nanometer range (1–100 nm) (Baig et al., 2021). Nanotechnology is the next great frontier in agricultural science, which focuses on enhancing agricultural production, improving the adaptive potential of plants to external stresses and is prominent in transforming agriculture, improving soil fertility, and producing food through efficient management of soil nutrients (Venkatachalam et al., 2017; Siddiqui et al., 2022). Devices derived from nanotechnology are widely applied in genetic transformation and plant breeding (Torney et al., 2007; Ahmar et al., 2021). The development of nanomaterials may find applications in soil science and soil nutrition (Duhan et al., 2017; Shweta et al., 2018). In addition, agriculture can also serve as a good source of bio-nanocomposites with improved physicomechanical properties based on traditionally harvested materials such as soybean hulls and wheat straw for bio-industry (Parisi et al., 2015; Sinclair et al., 2018).

In agriculture, nanotechnology improves crop productivity by increasing water use efficiency, the absorption of nutrients from the soil or plant, defence against insects and pests, fungal infections and diseases, creating innovative tools for pathogen detection, and environmental protection (Duhan et al., 2017; Ojha et al., 2018). Nanoparticles (NPs) in the form of encapsulated fertilisers increase the uptake and transport of nitrogen, phosphorus, and potassium for seeds. Therefore, nanotechnology is a prospect for the rapid development of agricultural practices (Ojha et al., 2018; Beig et al., 2022). Nanotechnology can solve the growing problem of nutrient scarcity due to the conversion of substances into biologically available forms (Morales-Díaz et al., 2017). Nanofertilisers have better catalytic ability and excellent water-adsorption properties. The structure and function of pesticides can be improved through nanomaterials by increasing their solubility and resistance against photodegradation and providing a more specific and controlled release to target organisms (Nuruzzaman et al., 2016). Therefore, nanofertilisers can increase the efficiency of nutrient, ion, and water uptake, ultimately improving the yield and nutrient content of edible parts of crop plants (Venkatachalam et al., 2017). In agriculture, the main concern for using nanotechnology consists of specific applications such as nanofertilisers and nanopesticides to increase plant growth and productivity without causing harm to the environment and protect against insects, pests, and microbial diseases.

## MATERIALS AND METHODS

This review summarises recent studies on various nanoparticles and their impact on soil quality, plant growth and development, stress tolerance, and questions concerning the synthesis, properties, and toxicity of nanomaterials used in agriculture. The gathered literature is mainly from the last ten years. The data was collected using the following keywords: a) nanoparticle or nanotechnology, stress, yield and field; b) nanoparticle, properties, activity and toxicity. The database is based on Google Scholar and PubMed searches.

## GENERAL PROPERTIES AND FUNCTIONS OF NANOPARTICLES

For an object to be defined as a nanoparticle, only one of its characteristic dimensions needs to be in the range 1–100 nm to be classified as a nanoparticle, even if it's other dimensions are outside this range. The lower limit of 1 nm is used because atomic bond lengths are reached at 0.1 nm (Baig et al., 2021). Table 1 presents some types of nanoparticles and summarises their use in agriculture.

### Silver nanoparticles

Silver nanoparticles (AgNPs) have a large surface area, a fraction of surface atoms, which leads to unique characteristics and properties such as high catalytic activity, reactivity, adsorption capacity and antimicrobial activity (Anchev et al., 2019). This crucial property of silver makes it an ideal alternative for various purposes in the medical and biotechnological fields (Salem et al., 2015). AgNPs are commonly used as an agent to protect crops from abiotic and biotic stress factors. Therefore, there is a growing interest in using AgNPs to reduce crop damage from insect infestation and plant disease management (Rai & Ingle, 2012). AgNPs can be synthesised by biological, chemical, electrochemical, photochemical, and physical methods (Banerjee et al., 2014; Salem et al., 2015). Biological methods are preferred because they are non-toxic and environmentally friendly (Duhan et al., 2017). The green approaches include obtaining AgNPs from plants, algae, and microorganisms (Bhattacharya & Gupta, 2005; Mohanpuria et al., 2008; Aziz et al., 2015; Saber et al. 2017). The biogenic synthesis of AgNPs was achievable from various plant extracts, for example, *Daucus carota* (Shanmuganathan et al., 2018), *Triticum aestivum* (Saratale et al., 2019), *Phoenix dactylifera* (Oves et al., 2018), *Mangifera indica* (Qayyum et al., 2017), *Phyllanthus emblica* (Masum et al., 2019) etc.

The biosynthesised AgNP has potent antibacterial activity and is effective against Gram-negative and Gram-positive bacteria due to neutralising the electrical charge on the surface of bacterial cell membranes, which changes their permeability and subsequently leads to cell death (Mehta et al., 2016; Prasad et al., 2017). AgNPs are effective against various fungal pathogens (Mansoor et al., 2021). The higher antifungal activity of silver is expressed in the inactivation of the sulfhydryl groups of fungal cell walls, thereby disrupting the transmembrane electron transport chain and accelerating energy metabolism (Duhan et al., 2017). AgNP efficacy depends on particle size and shape, surface coverage, concentration, and duration of exposure, as well as plant species and developmental stage, and decreases with increasing particle size (Jhanzab et al., 2015). The hormetic effect of the application of AgNPs was observed: the specific concentration promoted plant growth compared to untreated plants, while higher and lower concentrations inhibited growth (Sichanova et al., 2022; Pahal et al., 2022). AgNPs scavenge free radicals formed in cells exposed to various environmental stressors and thus facilitate the stabilisation of cellular macromolecules and improve plant health and agricultural production, respectively (Yadu et al., 2018). AgNPs affect plant growth and development processes, including germination, root growth, root elongation, root-shoot ratio, and senescence inhibition (Jhanzab et al., 2015; Yadu et al., 2018). This may be due to the high specific surface area of AgNPs, which may be responsible for the release of nutrient ions on their surfaces, thereby serving as a nutrient supplier for germinating seeds and supporting their growth (Banerjee et al., 2014). There is evidence for significant increases in all photosynthetic pigment contents in plants (chlorophyll a, chlorophyll b, carotenoids, and total pigments) in response to treatment with different concentrations of AgNPs, which corresponds to the change in nitrogen metabolism (Latif et al., 2017; Sadak, 2019). The concentration of amino acid silver nanofibers in the nutrient medium was found to affect the growth and steviol glycoside production in *Stevia rebaudiana in vitro* plants (Sichanova et al., 2022). In agriculture, AgNP can reform the field by increasing the efficiency of plants to absorb and move more nutrients, which activates the antioxidant defence system and thus exhibits greater resistance to various environmental stresses, which ultimately improves crop yield (Yadu et al., 2018).

**Zinc nanoparticles**

Zinc (Zn) is one of the essential trace elements for plants, animals, and humans (Cakmak & Kutman, 2018). Its deficiency is considered one of the leading risk factors, as it causes severe health disorders in infants and the development of chronic diseases in youth (Pavithra et al., 2017). Most crops also suffer from zinc deficiency, and almost all plants respond positively to Zn application (Hassan et al., 2017). In plants, this deficiency leads to a micronutrient crisis that adversely affects agricultural production in highly alkaline calcium carbonate soils (Duhan et al., 2017). The parameter that limits Zn availability to plants in calcium carbonate soils is alkaline pH, which reduces Zn solubility and increases the content of calcium carbonates that can absorb and precipitate Zn (Rashid & Ryan, 2004). The application of Zn oxides and sulfates as Zn fertilisers is limited due to the problematic absorption of Zn by plants, so their deficiency in the soil cannot be overcome (Ali et al., 2021). The use of zinc nanoparticles (ZnNPs) delivers a more soluble and accessible form of Zn to plants due to their higher reactivity (Duhan et al., 2017). Using these NPs, Zn can quickly diffuse from fertilisers to plant tissues thus overcoming Zn deficiency (Gangloff et al., 2006). Zn is related to protein synthesis, metabolism of carbohydrates, lipid, and nucleic acid synthesis, as well as participating in Cu-Zn-SOD enzyme synthesis, which is a crucial enzyme involved in the removal of toxic oxygen radicals (Lenka & Das, 2019; Semida et al., 2021). ZnNPs are preferable because they are more cost-effective and environmentally friendly than chemically synthesised NPs (Duhan et al., 2017). The experimental procedure included using a plant extract from weed plants dissolved in solvents such as water. Ethanol or methanol is used for ZnNPs synthesis, which is mixed with suitable aqueous solutions of zinc sulfate heptahydrate or zinc acetate dehydrate at an appropriate pH. It has been shown that these nanoparticles have good antifungal and bactericidal effects and are environmentally friendly (Rajiv et al., 2013). Owing to their small size (below 100 nm) and high surface-to-volume ratio, ZnNPs show much better antimicrobial activity and allow better interaction with soil bacteria (Xie et al., 2011). The antimicrobial activity of 16- to 20-nm sized ZnNPs synthesised from *Moringa oleifera* leaf extract, is effective against a variety of bacterial strains such as *Escherichia coli*, *Bacillus subtilis*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa* and fungal strains such as *Candida albicans* and *Candida tropicalis* (Elumalai et al., 2015). Furthermore, as has been reported by Rajiv et al. (2013), ZnNPs synthesised from *Parthenium hysterophorus* leaves show antifungal activity against plant pathogens such as *Aspergillus favus* and *Aspergillus niger*. Enhancement of biomass of shoots and roots has been reported in sunflower, *Pennisetum americanum* L., *Vigna radiata* (L.), *Brassica napus* L. using ZnNPs (Dhoke et al., 2013; Tarafdar et al., 2014; Torabian et al., 2016; Sawati et al., 2022). The foliar application of biogenic ZnNPs influences the expression of genes associated with photosynthesis, ribosome structural constituents, and the oxidative stress response of *Brassica napus* varieties (Sawati et al., 2022). Using ZnNPs in agriculture is efficient for plant growth acceleration, nutrition, and the fight against diseases and pests.

**Silicon nanoparticles**

The biological role of Si is known to be related to the improvement of cell growth and the development of diatoms, fungi, and corals. Si is ubiquitous and is present in all life forms. Higher plants absorb Si from aqueous solutions more efficiently than other nutrients. It is known to regulate defence mechanisms in plants against various abiotic (drought, salinisation, heavy metals) and biotic (insects, pests, diseases, etc.) stresses (Alsaeedi et al., 2017; Rastogi et al., 2019). The exogenous application of SiNPs plays a role in ameliorating toxicity induced by abiotic stress in crop plants and represents an innovative tool for pathogen detection and environmental management (Tripathi et al., 2015, 2016). The use of silicon increases the activity of the antioxidant system and the efficient use of water by lowering evaporation. Thus, it has been widely used in nanotechnology to create SiNPs to increase the productivity and quality of crops (Siddiqui & Al-Whaibi, 2014). It has been reported that under stress conditions, seed germination rate, growth, and biomass accumulation of crop plants improve (Alsaeedi et al., 2017). SiNPs effectively reduce the uptake and accumulation of heavy metals; increase the levels of macro- as well as micronutrients; reduce the accumulation of free radicals; stabilise the photosynthetic apparatus; mitigate oxidative damage to the plasma membrane; have an improved enzymatic antioxidant defence system; correct the levels of non-enzymatic antioxidants, etc. (Tripathi et al., 2015, 2016). SiNPs were found to release Si, which was deposited under the cuticle layer of the leaves, thus reducing the transpiration rate and maintaining a higher relative water content in the leaves. The application of SiNPs in agriculture increases sustainability and improves the productivity of crops. Silica nanoparticle-mediated targeting of biomolecules would be useful for developing new cultivars resistant to various biotic and abiotic factors (Rastogi et al., 2019). These nanoparticles can provide green and environmentally friendly alternatives to chemical fertilisers without harming nature. Thus, SiNPs may have specific solutions for many agricultural problems regarding weeds, pathogenicity, drought, crop yield, and productivity.

**Titanium nanoparticles**

Titanium (Ti) or titanium dioxide ($TiO_2$) NPs are considered an environmentally friendly and clean photocatalysts because of their optical characteristics, chemical stability, and non-toxic nature and because they can be synthesised in a natural way (Anucha et al., 2022). Titan nanoparticles have been shown to improve various plant species' germination rate and growth (Morteza et al., 2013; Kolenčík et al., 2020).

$TiO_2$NPs promote cell division, delay senescence through changes in pythohormonal levels in some plants and affect the oil content and maturation of sunflowers (Kolenčík et al., 2020; Landa, 2021). $TiO_2$NPs improve photosynthetic pigments in plants (chlorophyll, carotenoids and anthocyanins content), thus increasing the yield and productivity of crops (Morteza et al., 2013). Insecticidal activity against several pests like red palm weevil, cotton leaf worm, *Bactericera cockerelli* Sulc has been reported (Al-Bartya & Hamza, 2015; Shaker et al., 2017; Gutiérrez-Ramírez et al., 2021). The scientific evidence for fungicidal and bactericidal activity against important fungi and phytopathogenic bacteria has been documented (Huang et al., 2013; Boxi et al., 2016). $TiO_2$NPs in agricultural plots show an increase in the activity of certain enzymes, promote nitrate absorption and the transformation of inorganic to organic nitrogen, nutrient mobilisation, biotic and abiotic stress tolerance (Arruda et al., 2015).

**Carbon nanotubes**

Carbon nanotubes (CNTs) are a new form of carbon with a cylindrical structure, and a two-dimensional graphene sheet rolled into a tubular configuration (Zaytseva & Neumann, 2016). They are categorised as single-walled nanotubes with an outer diameter of 0.8–2 nm and multi-walled nanotubes with an outer diameter of 5–20 nm (De Volder et al., 2013). CNT lengths vary from 100 nm to several centimetres, depending on the desired application in various fields such as optics, nanomedicine, electronics, biosensors, etc. (Mukherjee et al., 2016). Owing to their outstanding unique optical, electrical, and magnetic properties and small size, these CNTs have attracted much attention in the past decade from scientists in the field of plant genetic engineering (Akhter et al., 2011). In agriculture, they have beneficial effects on seed germination, early plant growth, pesticides, and biosensor diagnostics and analysis (Patel et al., 2020). There are reports on the positive and negative effects of CNTs on various plant physiological processes and the growth and development of different vegetable crops. A decrease in the yield of zucchini and rice has been recorded as well as an increase in root growth in onions and cucumbers (Stampoulis et al., 2009; Lin et al., 2009). The ability of CNTs to penetrate the seed coats of tomato, corn, barley, and soybean, thus influencing the germination and growth of seedlings, has been reported (Khodakovskaya et al., 2009; Lahiani et al., 2013). Applying metal/metal oxide NP nanosensors based on electrochemically functionalised single-walled CNTs is very effective in monitoring agricultural pollutants and assessing their impact on living matter or health and increasing crop productivity and yield (Sekhon, 2014). Silver-coated CNT hybrid NPs show antimicrobial activity. In particular, single-walled CNTs show the most potent antifungal activity (Zaitseva & Neumann, 2016). Regulation of aquaporin genes upon CNT exposure has been found by Khodakovskaya et al. (2013), as CNTs have also been shown to be involved in water transport, cell division, and cell wall formation.

**Quantum dots**

The semiconductor nanocrystal quantum dots (QDs), also known as “artificial atoms”, were the first nanotechnology to be used in the life sciences and have found widespread application in many clinical and commercial products (Valizadeh et al., 2012). QDs have unique electronic and fluorescence characteristics such as narrow emission spectra, high photochemical stability, and continuous absorption spectra (Bruchez et al., 1998). These outstanding optical and electrical characteristics associated with the small size and large surface area make them ideal for biomedical and biotechnological use (Kuzyniak et al., 2014).

Before using QDs in biological applications, we need to evaluate their ecotoxicological data. Cd-based is mainly due to the release of Cd2+ upon particle surface oxidation (Derfus et al., 2004). QDs may cause DNA damage and suppression of cell proliferation (Hoshino et al., 2004) induce cell damage and even lead to cell death (Shiohara et al., 2004). Alimohammadi et al. (2011) have added QDs to nanotubules and significantly altered tomato plants’ viability by dramatically reducing root inhibition and leaf senescence. QDs are used to label plant proteins and thus are widely used in detecting pathogens associated with several diseases (Chahine et al., 2014).

Navarro et al. (2012) have reported oxidative stress in Arabidopsis roots after applying QDs. Adsorption of water-soluble CdSe/ZnS QDs to the cell surface of *Chlamydomonas algae* reduced their photosynthetic abilities (Lin et al., 2009). The fate and transport of QDs in soil, plants and insects have shown that QDs can be transported in the environment (Al-Salim et al., 2011).

In nanotechnology, quantum dots (QDs) have started as promising innovative tools for basic and applied life sciences (Chakravarty et al., 2015). Due to their unique optical properties, QDs are much better and faster than organic fluorescent dyes due to their more efficient luminescence, small characteristic emission spectra, outstanding photostability and durability according to particle size and material composition and can be more effectively applied in biosensors (Jaiswal & Simon, 2004). The use of QDs is a proven advantage in the field of food technology. For the chemical conversion of water molecules into hydrogen, QDs have been used as a photocatalyst in the solar fuel pathway (Jaiswal & Simon, 2004). The exogenous applications of QDs at deficient concentrations have not revealed any toxic effects and have also proved to be a plant growth regulator (Chakravarty et al., 2015). Hence, QDs can be applied as intelligent treatment delivery systems to regulate seed germination and seedling development. They can easily enter plant cell walls due to their smaller size than cell wall pores. In addition, QDs can be used for bioimaging in plant root systems to probe known physiological processes (Duhan et al., 2017). It has been established that carbon QDs affect the elongation of root and stem, biomass accumulation and enhance the carbohydrates content and photosynthesis of the mung bean sprouts (Wang et al., 2018; Zhang et al., 2018). Early studies show that the exogenous application of graphene QDs increases the growth rate of *Coriandrum sativum* and involves the production of proteins essential for plant development. Their survey on QDs has revealed that the application of QDs increased average root length and weight with improvements in leaf size, vigour, and green colour compared to untreated *Coriandrum sativum* (Chakravarty et al., 2015).

## NANOMATERIALS

### Nanopesticides

Implementing engineered nanomaterials is an efficient and novel technology in the field of biopesticides. In the agronomic sector, it is well known that insects and pests adversely affect crop growth and productivity in general (Ghormade et al., 2011). That is why conventional pesticides are widely used to improve crop protection and production, food quality and preservation, and domestic use. Due to the harmful effect of synthetic pesticides on animals and humans, they have been replaced by alternative biopesticides for pest control (Chhipa, 2017; Duhan et al., 2017). There are two types of biopesticides: biochemical biopesticides (natural compounds used for pest management) and biocontrol organisms (microbial fungi) (Kumar and Singh, 2015). Nanopesticides produced by nanotechnology are also used in agriculture for pest control to reduce the environmental footprint of a pesticide (e.g. using materials that have a physical form with at least one size dimension in the 1−100 nm range). Nanopesticides can be conventionally divided into tiny particles of the pesticide's active ingredient or other small engineered structures with beneficial pesticide properties (Kookana et al., 2014). They have a crucial role due to their typical properties such as increased solubility, specificity, stability and bioavailability to protect against premature degradation and for controlled release based on light, pH, humidity and temperature of active ingredients (Thakur et al., 2018). It is essential to improve agricultural production by synthesising and putting into operation non-toxic and environmentally friendly systems with pest/insect control properties such as nanopesticides, which will not only be a better substitute for pesticides, but also be useful in reducing the destructive impact of toxic chemicals on the environment. The nanopesticide in the form of a pesticide delivery system is designed to transport and deliver the active substance to a specific target at specific durations and concentrations to achieve the intended biological efficacy while minimising harmful effects on non-target organisms (Ghormade et al., 2011). Nanocarriers such as polymer nanoparticles and solid inorganic nanoparticles (synthetic silicon dioxide nanoparticles, titanium, silver, aluminium oxide and copper) are most often used as carriers of pesticides (Barik et al., 2008; Kah et al., 2013; Deka et al., 2021). Some nanoparticles possess insecticidal properties and can be used as nanocarriers and as active agents for pest control. Due to the electrostatic interaction of nanoparticles with bacterial cell membranes and their accumulation in the cytoplasm, most metal-containing NPs exhibit good antibacterial, antifungal and antipathogenic activity (Bansal et al., 2014). Nanomaterials, including silver, silver oxide, gold, ZnO, $TiO_2$, magnesium oxide (MgO), and copper oxide (CuO) NPs possess antimicrobial activity. Therefore, they have been widely investigated for their insecticidal, bactericidal and fungicidal activity against phytopathogens, alone or in combination with other metal NPs (Agrawal & Rathore, 2014). Due to their diverse modes of inhibition, these NPs inhibit or slow the growth of several pathogens and can be used as novel antimicrobial agents as an alternative to synthetic pesticides (Ghormade et al., 2011). It has been suggested that AgNPs are toxic to many plant pathogens. They are considered powerful nanopesticides because they inhibit microbial growth by inhibiting the germination of their spores. For example, the treatment of *Tinea pellionella* case-bearing cloth moths' larvae with an ethanol-based nanosilver colloid (<20 ppm) leads to 100% mortality (Ki et al., 2007). In a three-day treatment of infected wheat, nanostructured alumina as a wettable powder resulted in more than 95% mortality of *S. oryzae* and *R. dominicum* (Stadler et al., 2009). Mondal & Mani (2012) have found that CuNPs show antibacterial activity against *Xanthomonas axonopodis* pv. *punicae* in *Punica granatum*. They bind to the nucleic acids of bacterial cells and cause intermolecular cross-linking. They also damage proteins by binding to their sulfhydryl groups and/or carboxyl groups of amino acids. In this way, the biological processes of the bacteria are hindered.

The application of nanomaterials has been found to improve plant health and agricultural production of atrazine and simazine (Nuruzzaman et al., 2016; Chhipa, 2017). Significant insecticidal activity of the essential oil of *Allium sativum* has been found by Yang et al. (2009) against *Tribolium castaneum* after using polyethylene glycol (PEG)-coated NPs. Anjali et al. (2012) have reported that *Azadirachta indica* oil nanoemulsion is an effective larvicidal agent against *Culex quinquefasciatus*. Therefore, nano-encapsulated pesticide formulation is quite effective than normal agrochemicals due to slow and sustained release, which allows proper absorption of the chemical in plants and has a long-lasting and sustainable effect (Ojha et al., 2018). The specificity of synthetic pesticides against targeted pests is high. Still, they have detrimental effects on human health and the environment, so there is an urgent need to expand the boundaries of using nanomaterials in insect/pest control (Ghormade et al., 2011).

**Nanocomposites**

Nanocomposites are heterogenous or hybrid composites synthesised by incorporating particles in the nanometer range obtained from standard material. They are composed of at least two components: (i) a matrix or continuous phase in which the nanosised particles are dispersed and (ii) the nanosised particles/nanoparticles constituting the second phase, i.e. the dispersed phase (Ojha et al., 2018).

The nanocomposite can be classified, depending on the matrix materials, into three groups: (1) metal matrix composites [$Ni/Al_2O_3$, $Fe\text{-}Cr/Al_2O_3$, Co/Cr, Fe/MgO, Al/CNT], (2) ceramic matrix composites ($Al_2O_3/SiO_2$, $Al_2O_3$/CNT, $SiO_2$/Ni, $Al_2O_3/TiO_2$, $Al_2O_3$/SiC) and (3) polymer matrix composites (polymer/CNT, polyester/$TiO_2$, polymer/layered silicates) (Camargo et al., 2009). Nanocomposites are produced and used in agriculture to enhance the efficiency of the main matrix material by improving its physical, chemical, and biological properties. For example, due to the presence of functional groups in the chemical structure of chitosan that easily react with other active compounds, chitosan-based nanomaterials are actively used for several applications in agriculture as nanoparticles, microbeads, microfibres (Sathiyabama & Parthasarathy, 2016; Yu et al., 2021). On the other hand, some studies have reported that metal-based nanomaterials widely used in agriculture also exhibit phytotoxicity (Wang et al., 2019; Young & Santra, 2014). Some researchers have combined chitosan composites with nanometals like silver (Ag), and the results have enhanced antimicrobial properties (Biao et al., 2017).

Nanocomposites have potential applications in plant growth and development and insect/pest management. Gunaratne et al. (2016) have investigated two plant food nanocomposites based on urea-coated hydroxyapatite (UHA) and potassium encapsulated into nanoclay or cavities in *Gliricidia sepium* stem resulting in a wood chip containing macronutrients. The authors have reported that both nanocomposites show slow nitrogen release behaviour in the soil compared to conventional fertiliser formulations. Both nanoformulations have shown effective uptake of nutrients by the *Festuca arundinacea* plant, highlighting improved nutrient utilisation efficiency. Ghassemi-Golezani et al. (2021) have investigated the combined effect of biochar and based metal oxide nanocomposites using solid biochar, biochar-based nanocomposites (BNCs) of magnesium oxide, manganese oxide and combined use of both nanocomposites on salt tolerance safflower plants (*Carthamus tinctorius* L.). The authors have reported that biochar and BNCs have a great potential for improving the plant's salt tolerance by an increase in the contents of potassium, manganese and magnesium in plant tissues, photosynthetic pigments, Fv/Fm and RETR, leaf water content, oxidative stress, which parameters are reduced under saline stress. Metal matrix nanocomposites consist of a metal alloy reinforced with nanosised materials. Positively charged metal nanocomposites such as AgNP, CuNP and TiNP interact with negatively charged cell walls/membranes of bacteria or fungi through electrostatic interactions, due to which they can change the properties of bacterial cell membranes by adhering to their surfaces possess antimicrobial activity (Rai & Ingle, 2012; Ojha et al., 2018; Romero-Fierro et al., 2022). The metal nanocomposites entering the microbial cells, bind to various cellular organelles, begin to disrupt the metabolic processes of the cells, and ultimately lead to the death of the microbe (Navarro et al., 2008a, b; Fabrega et al., 2009; Tripathi et al., 2017a, b).

## NANOTOOLS IN AGRICULTURE

Agricultural crops are among the sources of vital nutrients in humans and animals (Rajput et al., 2021). Modern agriculture requires high productivity per unit area, which is impossible without using agrochemicals such as pesticides and fertilisers. However, there are potential problems associated with agrochemicals that negatively affect human health and the environment. Furthermore, larger quantities of fertilisers do not mean higher yield; many fertilisers have low availability for plants due to decomposition, hydrolysis, and leaching, the latter of which leads to the risk of contamination of surface and groundwater resources (Chhipa, 2017; Duhan et al., 2017; Chhipa, 2019; Sadak, 2019). Innovations in nanotechnology offer more productive, cost-effective, and environmentally friendly ways to address these challenges. Nowadays, nanotools such as nanocomposites, nanosensors, nanofertilisers, nanopesticides, and nanoherbicides are increasingly used for the improvement of both the quantity and quality of crops, and at the same time for the reduction and/or elimination of the harmful effects of agrochemicals on the environment (Parisi et al., 2015; Manjunatha et al., 2016; Prasad et al., 2017; Chhipa, 2017). Nanomaterials find their application in agricultural practices: 1) by stimulating seed germination and plant growth; 2) as a delivery system for plant growth regulators; 3) as a tool for plant genetic engineering; 4) as nanofertilisers and nanopesticides; and 5) for plant pathogen detection and crop protection (Ahmad et al., 2022). The exogenous application of specific NPs can act as a potent agent against various abiotic stresses such as heavy metals (Venkatachalam et al., 2017), arsenic (Praveen et al., 2018), fluoride (Yadu et al., 2018), etc. by inducing a wide range of processes involved in plant defence mechanisms (Praveen et al., 2018). For example, ZnO NPs play an essential role in protecting plants against oxidative damage provoked by reactive oxygen species (ROS) by increasing gene expression and the activity of antioxidant enzymes. $TiO_2$ NPs can enhance photosynthesis, biomass accumulation, and antioxidant defence, which helps plants increase their growth potential and salinity tolerance (Abdel Latef et al., 2018). The positive effect of NPs on plant growth may be due to: (i) NPs-mediated reduction in the accumulation of toxic metals in plants; (ii) reduced level of free radicals and oxidative damage caused by different stress factors; (iii) activation of plant antioxidant defence system; and (iv) increased levels of macro- and micronutrients available to plants (Tripathi et al., 2016). Furthermore, nanomaterials regulate the expression of water channel genes (aquaporins) and thus play an important role in permeability and improving water status and nutrient uptake during seed germination (Lahiani et al., 2016; Singh et al., 2019).

## SOURCES AND PHYTOTOXICITY OF NANOPARTICLES

Nanomaterials originate from both natural and anthropogenic sources. Nanoparticles' natural sources

Table 1. Summary of nanoparticle types and their application in agriculture

| Nanoparticles | Application in agriculture | Reference |
|---|---|---|
| Silver nanoparticles | ➢ protect crops from abiotic and biotic stress; activates the antioxidant defence system | Yadu et al., 2018 |
| | ➢ reduce crop damage from insect infestation and plant disease management | Salem et al., 2015 |
| | ➢ antibacterial activity against Gram-negative and Gram-positive bacteria | Prasad et al., 2017 |
| | ➢ antifungal activity | Duhan et al., 2017; Mansoor et al., 2021 |
| | ➢ stimulate plant growth and development, including germination, root growth, root elongation, root-shoot ratio, and senescence inhibition | Jhanzab et al., 2015; Yadu et al., 2018 |
| | ➢ significant increases in all photosynthetic pigment contents in plants (chlorophyll a, chlorophyll b, carotenoids, and total pigments) | Latif et al., 2017; Sadak, 2019 |
| | ➢ secondary metabolites enhancement; hormetic effect on growth | Sichanova et al., 2022 |
| Zinc nanoparticles | ➢ increase agricultural production | Duhan et al., 2017 |
| | ➢ soil quality improvement; easily diffuse from fertilisers to plant tissues and thus overcome Zn deficiency | Gangloff et al., 2006; Ali et al., 2021 |
| | ➢ antimicrobial activity effective against several bacterial and fungal strains | Xie et al., 2011; Rajiv et al., 2013; Elumalai et al., 2015 |
| | ➢ accelerates plant growth and nutrition | Dhoke et al., 2013; Tarafdar et al., 2014; Torabian et al., 2016 |
| | ➢ influence the expression of genes associated with photosynthesis, ribosome structural constituents, and oxidative stress response | Sawati et al., 2022 |
| Silicon nanoparticles | ➢ regulate defence mechanisms in plants against various abiotic stresses (drought, salinisation, heavy metals); reduce the accumulation of free radicals; mitigate oxidative damage to the plasma membrane, an improved enzymatic antioxidant defence system | Alsaeedi et al., 2017; Tripathi et al., 2015, 2016 |
| | ➢ increase biotic stresses tolerance (insects, diseases, etc. pests) | Rastogi et al., 2019 |
| | ➢ efficient use of water by lowering evaporation | Tripathi et al., 2015 |
| | ➢ improves seed germination rate, growth and biomass accumulation of crop plants | Alsaeedi et al., 2017 |
| | decrease the uptake and accumulation of heavy metals | Tripathi et al., 2016 |
| | ➢ increase the levels of macro- as well as micronutrients | Tripathi et al., 2015 |
| Titanium nanoparticles | ➢ positive effect on the germination rate and growth of various plant species | Morteza et al., 2013, Kolenčík et al., 2020 |
| | ➢ promote cell division and delay senescence through changes in levels of plant hormones | Kolenčík et al., 2020; Landa, 2021 |
| | ➢ improve photosyntethic pigments in plants (chlorophyll, carotenoids and antocyanins content) | Morteza et al., 2013 |
| | ➢ insecticidal activity | Al-Bartya & Hamza, 2015; Shaker et al., 2017; Gutiérrez-Ramírez et al., 2021 |
| | ➢ fungicidal and bactericidal activity | Huang et al., 2013, Boxi et al,. 2016 |

| Nanoparticles | Application in agriculture | Reference |
| --- | --- | --- |
| | ➢ promote nitrate absorption and the transformation of inorganic to organic nitrogen, nutrient mobilisation | Arruda et al., 2015 |
| Carbon nanotubes | ➢ penetrate the seed coats, thus influencing the germination and growth of seedlings | Lahiani et al., 2013 |
| | ➢ monitoring agricultural pollutants | Sekhon, 2014 |
| | ➢ increasing crop productivity and yield | Sekhon, 2014; Stampoulis et al., 2009 |
| | ➢ antimicrobial and antifungal activity | Zaitseva and Neumann, 2016 |
| | ➢ participation in water transport, cell division, and cell wall formation | Khodakovskaya et al., 2013 |
| | ➢ beneficial early plant growth, pesticides, and biosensor diagnostics and analysis | Patel et al., 2020 |
| Quantum dots | ➢ DNA damage and suppression of cell proliferation | Hoshino et al., 2004; Shiohara et al., 2004 |
| | ➢ reducing root inhibition and leaf senescence | Alimohammadi et al., 2011 |
| | ➢ label plant proteins and use in the detection of pathogens | Chahine et al., 2014 |
| | ➢ photocatalyst in the solar fuel pathway | Jaiswal & Simon, 2004 |
| | ➢ innovative treatment delivery systems to regulate seed germination and seedling development | Chakravarty et al., 2015 |
| | ➢ increase the growth rate and production of proteins essential for plant development | Chakravarty et al., 2015<br>Zhang et al., 2018 |
| | ➢ affect the elongation of root and stem, biomass accumulation and enhance the carbohydrates content and photosynthesis | Wang et al., 2018 |
| Nanopesticides | ➢ increase solubility, specificity, stability and bioavailability of nutrients | Thakur et al., 2018 |
| | ➢ designed to transport and deliver the active substance to a specific target at specific durations and concentrations to achieve the intended biological efficacy while minimising harmful effects on non-target organisms | Ghormade et al., 2011 |
| | ➢ exhibit good antibacterial, antimicrobial and antifungal activity | Bansal et al., 2014; Agrawal & Rathore, 2014; Ghormade et al., 2011 |
| | ➢ improve plant health and agricultural production | Nuruzzaman et al., 2016; Chhipa, 2017 |
| | ➢ a slow and sustained release, which allows proper absorption of the chemical in plants and has a long-lasting and sustainable effect | Ojha et al., 2018 |
| Nanocomposites | ➢ nanocomposites based on urea-coated hydroxyapatite and potassium show slow nitrogen release behaviour in the soil compared to conventional fertiliser formulations | Gunaratne et al., 2016 |
| | ➢ biochar-based nanocomposites have a great potential for improving the plant's salt tolerance by an increase in the contents of potassium, manganese and magnesium in plant tissues, photosynthetic pigments, leaf water content, oxidative stress | Ghassemi-Golezani et al., 2021 |
| | ➢ metal nanocomposites entering the microbial cells, bind to various cellular organelles, begin to disrupt the metabolic processes of the cells, and ultimately lead to the death of the microbe | Navarro et al., 2008a, b; Fabrega et al., 2009; Tripathi et al., 2017a, b |

include photochemical reactions, volcanic eruptions, forest fires, erosions, and plant and animal metabolism (Remédios et al., 2012). Additionally, human activities may lead to the immediate and/or accidental release of vast amounts of engineered NMs into the environment. Most have finally accumulated in the soil (Keller et al., 2013). This, in turn, affects soil health, microbiome, and plant health (Khan et al., 2021). Many articles regarding the impact of NPs on the ecosystem have been published, and almost no effect is observed when NMs are used in lower doses. However, more studies are needed for a better understanding of the behaviour of NMs under real-world conditions. The size, shape, composition, surface chemistry, and concentration of nanoparticles determine their toxicity (Zhang et al., 2015; Khare et al., 2015*;* Madanayake & Adassooriya, 2021). Nanoparticles possessing a higher surface area to volume ratio than the corresponding bulk materials can be highly reactive (Rico et al., 2011). Their absorption is estimated to be 15–20 times higher than the respective bulk particles (Zhao et al., 2012). Most studies focus on the effect of NPs in laboratory or greenhouse conditions, but little is known about the fate of nanoparticles after their interaction with various soil components such as minerals, colloids, and soil organic matter as well as after entering plant organisms. Nanoparticles may enter the plant body via roots or through aerial parts with water and air and can be transported to different parts of the plant via apoplast or symplast and by upward or downward movement (Rizwan et al., 2017). Metal NMs such as Zn, Cu, Fe, Mn, Ag and their oxides (ZnO, CuO, $TiO_2$) have been intensively studied for their phytotoxicity in different model plants (Madanayake & Adassooriya, 2021). According to Peng et al. (2015), CuO NPs induce inhibition of root elongation and abnormalities in root morphology. Dimkpa et al. (2012) have reported CuO NPs and ZnO NPs mediated reduction in root and shoot growth of wheat. The authors have suggested that CuO and ZnO NPs negatively affect photosynthesis by reducing the chlorophyll content. Treatment of *Allium cepa* plants with 5 and 50 µg/mL ZnO NPs have shown cytotoxic and genotoxic effects in the root meristems by affecting cell membrane integrity, metabolic activity, reactive oxygen species accumulation, DNA damage, chromosome aberrations, and cell cycle progression (Sun et al., 2019). Reduced biomass production, suppressed carbohydrate synthesis, elevated levels of respiration, and a disturbed antioxidant defence system have been observed in rice treated with $TiO_2$ NPs (Wu et al., 2017). Frazier et al. (2014) have found that higher concentrations of $TiO_2$ NPs significantly inhibit the germination rate, root length, and biomass accumulation in tobacco seedlings. $TiO_2$ NPs have been reported to inhibit root water transport and transpiration by reducing the pore diameter of cell walls (Asli & Neumann, 2009). Furthermore, $TiO_2$ NPs could induce chromosomal abnormalities and reduce the mitotic index in maize (Castiglione et al., 2011). Raised $H_2O_2$ production, lipid peroxidation, and electrolyte leakage have been reported in rice plants under higher concentrations of $CeO_2$ NPs (Rico et al., 2011).

## FUTURE PERSPECTIVES ON USING GREEN SYNTHESISED NANOPARTICLES IN THE FIELD OF SUSTAINABLE AGRICULTURE

New technologies are increasingly being implemented in agriculture science to increase the quality and production of cultivated crops. Nanoparticles are usually produced using chemical methods, and studies show that using a chemical-reducing agent consumes more energy and generates larger-sized particles. Considering the toxic effects on human well-being in using synthetic materials changed the direction of the researchers' investigations. Presently, green synthesis is the watchword for combining nanoparticles (NPs) by plants or their metabolites. This innovation compensates exceptionally for decreasing the poisonous quality caused by the conventionally integrated NPs. Plant metabolites and natural substances are utilised in the green strategies to orchestrate the NPs for agronomic sector applications. The biological/green synthesis methods can produce stable and dispersible NPs of the desired size by consuming comparatively less energy.

## CONCLUSIONS

In agriculture, we face various challenges due to the growing world population and climate change. Agriculture is an essential source of human food. The application of modern nanotechnologies in agriculture can significantly contribute to the sustainable growth of this critical sector. The application and concentration of NPs to stimulate growth, stimulate physiological processes, and induce toxicity vary depending on the plant species and growth stage. Plant-specific tests must determine whether a particular NP is beneficial or detrimental to plant growth and performance. The indiscriminate nature of the applied NPs may limit their effectiveness as a nanofertiliser. In the long term, this technology may provide innovative and economic avenues for developing human nutrition worldwide. New and upcoming technology is nanotechnology, which has a unique property in the food supply chain throughout the agricultural sector worldwide.

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