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REVIEW **Open Access**

Green nanotechnology: illuminating the effects of bio-based nanoparticles on plant physiology

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Abstract

The use of bio-based nanoparticles in agriculture has gained significant attention due to their potential to enhance plant development, growth, and differentiation. This review aims to provide a comprehensive overview of the impact of bio-based nanoparticles on plant physiology. In this review paper, the various types of bio-based nanoparticles, including cellulose, chitosan, and lignin nanoparticles, and their effects on plant growth and development were discussed. The mechanisms by which these nanoparticles interact with plants at the cellular and molecular levels were also examined. Furthermore, the potential applications of bio-based nanoparticles in agriculture, such as improving nutrient uptake, enhancing stress tolerance, and promoting sustainable crop production, are also highlighted. Overall, this review provides valuable insights into the potential benefits of utilizing bio-based nanoparticles for enhancing plant growth and development while also considering their potential environmental impacts.

Keywords Nanoparticle, Biomaterial, Environmental impact, Plant growth, Plant stress

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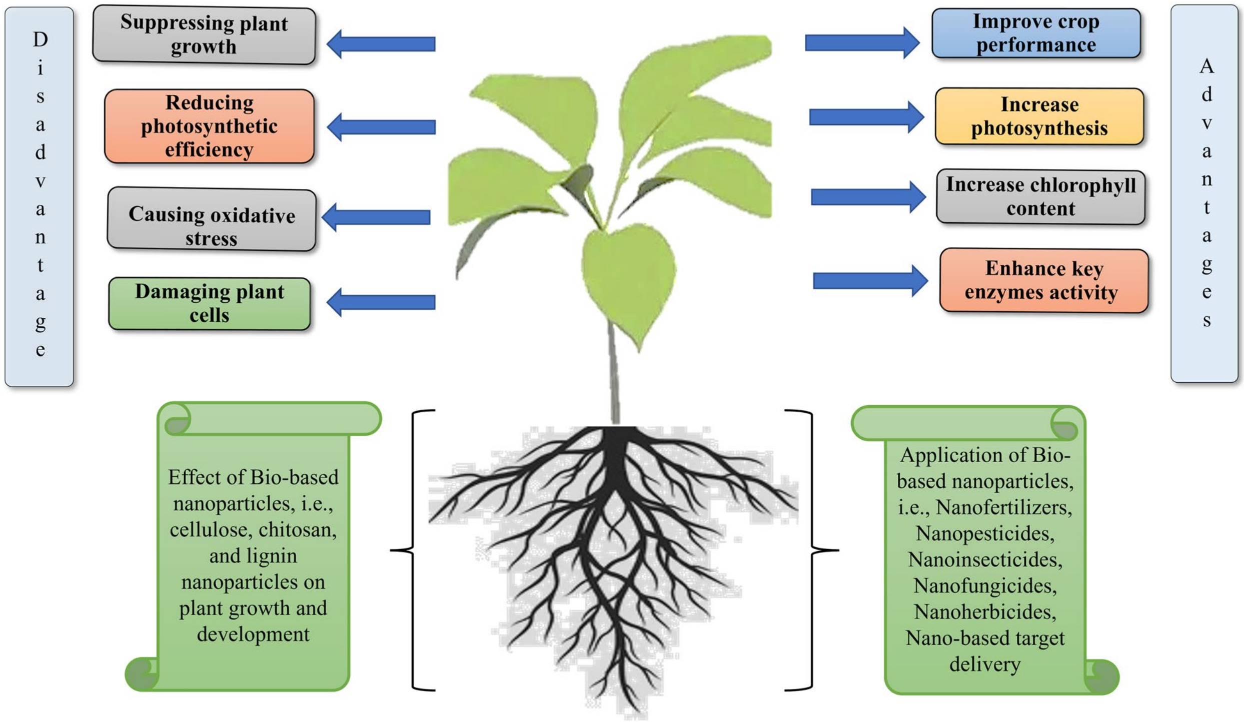
Graphical Abstract



Introduction

Bio-based nanoparticles have emerged as a promising tool in the field of plant science due to their unique properties and potential applications. These nanoparticles, derived from natural sources such as plants, bacteria, or fungi, offer several advantages over conventional materials. They possess a high surface area-to-volume ratio, excellent stability, and biocompatibility, rendering them appropriate for various plant-related applications [1].

Bio-based nanoparticles (i.e., cellulose, chitosan, and lignin nanoparticles), derived from renewable and biodegradable sources, have gained significant attention in agriculture due to their potential to enhance plant growth and development while minimizing environmental impacts. These nanoparticles possess unique properties that enable them to interact with plants at the cellular and molecular levels, influencing various physiological processes and improving overall plant performance. This article provides an overview of recent literature, highlighting examples of various bio-based nanoparticles and their multifaceted roles in plant growth and development. Cellulose nanoparticles, extracted from plant cell walls, have emerged as promising bio-based nanoparticles for agricultural applications. Their unique properties, i.e., high surface area, crystallinity, and biodegradability, make them suitable for various applications [2]. Cellulose nanoparticles have been shown to enhance nutrient uptake by increasing root surface area and facilitating the transport of nutrients into plant cells. Improve stress tolerance by activating defense mechanisms and regulating gene expression, enabling plants to better withstand environmental stresses like salinity, drought, as well as extreme temperatures. Promote plant growth and development by stimulating cell division, hormone production, and photosynthesis, resulting in increased biomass and yield [2].

Chitosan nanoparticles, derived from chitin, a natural polymer found in crustacean shells and fungal cell walls, have demonstrated promising effects on plant growth and development. Their inherent antimicrobial and antioxidant properties contribute to their beneficial roles in agriculture; Chitosan nanoparticles exhibit antifungal and antibacterial activity, protecting plants from various pathogens. They enhance nutrient uptake by chelating metal ions and facilitating their absorption by plant roots. Chitosan nanoparticles promote root development and improve seed germination by stimulating cell division and enhancing water retention [3].

Lignin nanoparticles, obtained from plant biomass, have garnered interest for their potential in sustainable agriculture. Their unique structure and properties contribute to their beneficial effects on plant growth and development. Lignin nanoparticles improve soil quality by enhancing soil structure, increasing water retention capacity, and promoting microbial activity. They facilitate nutrient uptake by increasing the surface area for nutrient adsorption and enhancing nutrient availability to plants. Lignin nanoparticles stimulate root development and promote plant growth by influencing hormone production and regulating gene expression [1].

In addition to cellulose, chitosan, and lignin nanoparticles, various other bio-based nanoparticles have shown promise in agriculture. These include Starch nanoparticles, which enhance seed germination, promote root development, and improve nutrient uptake. Protein nanoparticles which facilitate nutrient delivery, improve stress tolerance, and enhance plant growth. Lipid nanoparticles that enhance nutrient encapsulation and delivery, improve stress tolerance, and promote plant growth [2].

Biobased nanoparticles, derived from natural sources i.e., animals, plants, and microorganisms, have gained significant attention in various fields due to their unique properties and advantages over chemical-based nanoparticles. Biobased nanoparticles offer a sustainable alternative to chemical-based nanoparticles as they are derived from renewable resources. This reduces the dependence on fossil fuels and minimizes the environmental impact associated with the production and disposal of chemical-based nanoparticles. Biobased nanoparticles are often biocompatible, meaning they are less likely to cause adverse effects when used in biological systems. This makes them suitable for applications in medicine, such as drug delivery systems or imaging agents, where compatibility with living organisms is crucial. Chemical-based nanoparticles may pose health risks due to their potential toxicity [3]. In contrast, biobased nanoparticles are generally considered safer because they are derived from natural sources and can be metabolized by living organisms more easily.

Biobased nanoparticles exhibit a wide range of properties that can be tailored for specific applications. They can be modified through surface functionalization or encapsulation techniques to enhance their stability, solubility, or targeting capabilities. The production of biobased nanoparticles can be cost-effective compared to chemical-based counterparts since the raw materials used are often readily available and relatively inexpensive. Biobased nanoparticles possess inherent functionalities that can be harnessed for various applications. For example, chitosan nanoparticles derived from crustacean shells have antimicrobial properties, making them suitable for use in food packaging or wound healing [3].

Chemical-based nanoparticle synthesis often involves hazardous chemicals as well as energy-intensive processes that contribute to pollution and carbon emissions. In contrast, biobased nanoparticle production methods typically have lower environmental footprints due to the use of natural resources and less energy-intensive processes. Biobased nanoparticles can be integrated into existing manufacturing processes without significant modifications or disruptions since they share similarities with conventional materials used in industries like cosmetics, textiles, and electronics [4].

Overall, the importance of biobased nanoparticles lies in their sustainable nature, biocompatibility, low toxicity profile, versatility, cost-effectiveness, enhanced functionality, reduced environmental impact, and compatibility with existing technologies. These advantages make them promising candidates for a wide range of applications across various industries while addressing concerns related to health risks and environmental sustainability associated with chemical-based alternatives [4–6].

This paper aims to explore the impact of bio-based nanoparticles on plant development, growth, and differentiation. It contributes to our understanding of how these nanoparticles can influence plant development, growth, and differentiation can be seen in Table 1.

This article differs from previously published articles by focusing specifically on bio-based nanoparticles. While previous studies may have examined the impact of different types of nanoparticles on plants, this article narrows its scope to those derived from biological sources. This distinction is crucial as bio-based nanoparticles are considered more environmentally friendly as well as sustainable compared to their synthetic counterparts. By delving into the effects of bio-based nanoparticles on plant biology, this article provides new information to readers. It may uncover novel mechanisms through which these particles interact with plants and shed light on their potential applications in agriculture, horticulture, or environmental remediation. Additionally, it may identify any potential risks or adverse effects associated with the use of bio-based nanoparticles in plant systems. [5, 6]

Bio-based nanoparticles: types and synthesis

Bio-based nanoparticles can be classified into various types based on their origin and composition. Some common types include cellulose nanocrystals (CNCs), chitosan nanoparticles (CSNPs), silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), and magnetic nanoparticles (MNPs) Table 2 [57, 58].

These nanoparticles could be synthesized with the help of different methods i.e., chemical reduction,

Table 1 List of nanoparticles along with its morphology, origin, size and applications

NPs	Morphology	origin	Size (nm)	Applications	References
Gold and silver	Spherical, triangular	*Aloe barbadensis* Miller (Aloe vera)	10–30	Cancer hyperthermia, optical coatings	[7]
Indium oxide	Spherical	*Aloe barbadensis* Miller (Aloe vera)	5–50	Solar cells, gas sensors	[7]
Silver	Spherical	*Acalypha indica*	20–30	Antibacterial activity against water-borne pathogens	[8, 9]
Silver and gold	Spherical, triangular, and quasi-spherical	Apiin extracted from henna leaves	39	Hyperthermia of cancer cells and IR-absorbing optical coatings	[10, 11]
Gold	Rod-shaped	*Avena sativa* (oat)	5–20 (pH 3 and 4),	–	[12]
Gold, silver, and silver-gold alloys	Spherical, triangular, hexagonal	*Azadirachta indica* (neem)	5–35 and 50–100	Remediation of toxic metals	[13, 14]
Gold and silver	Spherical, prism	*Camellia sinensis* (leaf extracts of black tea)	20	Catalysts, sensors	[3, 6]
Silver	Spherical	*Brassica juncea* (mustard)	2–35	–	[15, 16]
Gold and silver	Quasi-spherical (Ag) and, triangular, spherical (Au)	*Cinnamomum camphora* (camphor tree)	55–80	–	[17, 18]
Silver	Spherical	*Carica papaya* (papaya)	60–80	–	[18]
Silver	Spherical, spheroidal	*Citrus limon* (lemon)	< 50	–	[19]
Gold	Spherical, decahedral, triangular, truncated triangular,	*Coriandrum sativum* (coriander)	6.75–57.91	Drug delivery, photothermal therapy, tumor/tissue imaging	[20]
Gold	Spherical, triangular	*Cymbopogon flexuosus* (lemongrass)	200–500	Infrared-absorbing optical coatings	[21]
Silver	Spherical	*Cycas sp.* (cycas)	2–6	–	[22]
bimetallic gold/silver	Cubic	*Diospyros kaki* (persimmon)	50–500	–	[23, 24]
Gold and silver	–	*Emblica officinalis*	(10–20) and (15–25)	–	[25, 26]
Silver	Spherical	*Eucalyptus citriodora* (neelagiri)	20	Antibacterial	[27]
Silver	Crystalline, spherical	*Eucalyptus hybrid* (safeda)	50–150	–	[28]
Silver	Spherical	*Garcinia mangostana* (mangosteen)	35	Antibacterial activity against *S. aureus* and *E. coli*	[29, 30]
Palladium	–	*Gardenia jasminoides Ellis* (gardenia)	3–5	Nanocatalysts for *p*-nitrotoluene hydrogenation	[31, 32]
Gold	Irregular	*Syzygium aromaticum* (clove buds)	5–100	Detection as well as destruction of cancer cells	[33, 34]
Silver	Spherical	*Jatropha curcas* (seed extract)	15–50	–	[35, 36]
Silver	Spherical	*Ludwigia adscendens* (ludwigia)	100–400	–	[37, 38]
Gold	Irregular, decahedral, tetrahedral, icosahedral, hexagonal platelet	*Medicago sativa* (alfalfa)	2–40	Labeling in structural biology paints	[13, 39]
Silver	Spherical	*Mentha piperita* (peppermint)	5–30	To kill microbes	[40]
Iron oxide	Crystalline	*Medicago sativa* (alfalfa)	2–10	Drug delivery, cancer hyperthermia	[41, 42]
Silver	Spherical	*Morus* (mulberry)	15–20	Antimicrobial activity against *E. coli*, *B. subtilis*	[43, 44]
Silver	Spherical, decahedral, truncated triangular, triangular	*Nelumbo nucifera* (lotus)	25–80	Larvicidal activity against malaria and filariasis vectors	[45, 46]
Silver	Spherical	*Ocimum sanctum* (root extract of tulsi)	10 ± 2 and 5 ± 1.5 nm	Catalytic reduction	[47, 48]

Table 1 (continued)

NPs	Morphology	origin	Size (nm)	Applications	References
Gold and silver	Crystalline, triangular, hexagonal, and spherical	*Ocimum sanctum* (leaf extract of tulsi)	30 and 10–20	Biolabeling, biosensor	[49, 50]
Gold	Triangular, hexagonal	*Pear fruit extract*	200–500	Catalysis, biosensing	[51]
Gold	Crystalline	*Pelargonium roseum*	2.5–27.5	–	[52]
Gold	Mostly spherical	*Psidium guajava* (guava)	25–30	–	[53]
Zinc oxide	Hexagonal wurtzite as well as pseudo-spherical	*Sedum alfredii* Hance	53.7	Nanoelectronics	[54]
Gold and silver	Triangular, spherical	*Tanacetum vulgare* (tansy fruit)	11, 16	Antibacterial, sensors	[55, 56]
Gold	Spherical	*Terminalia catappa* (almond)	10–35	Biomedical field	[52]

Table 2 This table provides an overview of the synthesis methods for nanoparticles of cellulose, chitosan, and lignin

Nanoparticle	Synthesis Method	Use	Examples	Reference
Lignin Nanoparticles	Anti-solvent precipitation, physicochemical methods (e.g., ultrasonication, homogenization)	Green fabrication of lignin nanoparticles/chitosan films for antibacterial activity	Spherical lignin nanoparticles, Lignin nanoparticles loaded with manganese dioxide	[1]
Cellulose Nanoparticles	Ultrasonication, other physicochemical methods	Preparation and applications of chitosan and cellulose composite materials	Cellulose nanocrystals, Cellulose nanofibrils, Bacterial nanocellulose	[59, 60]
Chitosan Nanoparticles	Incorporation into composite materials	Review on nanocomposite materials from cellulose, chitosan	Chitosan-TPP nanoparticles Lignin nanoparticles/chitosan films	[2]

green synthesis using plant extracts or microorganisms, or physical methods like sonication or ball milling [61]. Bio-based nanoparticles, also known as green nanoparticles, are a class of nanoparticles that are derived from natural sources such as plants, animals, and microorganisms [6]. These nanoparticles have gained significant attention as a result of being environmentally friendly in nature and potential applications in various fields, including medicine, agriculture, and environmental remediation [5, 62].

There are several types of bio-based nanoparticles that can be synthesized from different natural sources. Some of the commonly studied types include cellulose nanoparticles, chitosan nanoparticles, protein-based nanoparticles, lipid-based nanoparticles, and nanocrystals derived from minerals [58, 63]. Cellulose nanoparticles are among one of the utmost extensively studied bio-based nanoparticles. It could be extracted from various plant sources, i.e., wood pulp, cotton fibers, and agricultural waste [64]. The synthesis of cellulose nanoparticles involves the breakdown of cellulose fibers into smaller particles using mechanical or chemical methods [65]. These particles possess distinctive characteristics such as high aspect ratio, excellent mechanical strength, and biodegradability, which make them suitable for applications in packaging materials, reinforcement agents in composites, and drug delivery systems [66, 67].

Chitosan nanoparticles are another type of bio-based nanoparticle that is a derivative of chitin, a natural polymer found in the exoskeletons of crustaceans such as shrimp and crabs. Chitosan has excellent biocompatibility and biodegradability properties, which make it appropriate for bio-medical applications, for instance, drug delivery systems and tissue engineering scaffolds [68]. The chitosan nanoparticle synthesis involves the conversion of chitosan into smaller particles using techniques like ionic gelation or emulsion cross-linking. Protein-based nanoparticles are synthesized from proteins obtained from various sources such as soybeans, milk proteins (casein), or silk fibers. These proteins can be modified to form stable nanoparticle structures through techniques like self-assembly or coacervation [69]. Protein-based nanoparticles have shown promising applications for drug delivery systems because of their capability to encapsulate drugs efficiently and protect them from degradation [12].

Lipid-based nanoparticles are synthesized using lipids extracted from natural sources such as vegetable oils or animal fats. These lipids can form various structures, including liposomes, solid lipid nanoparticles (SLNs), or nano-emulsions, depending on the synthesis method employed [70]. Lipid-based nanoparticles have been widely investigated for drug delivery applications due to their ability to encapsulate both hydrophilic and hydrophobic drugs effectively. Nanocrystals derived from minerals are another type of bio-based nanoparticle that can be synthesized by extracting minerals from natural sources like clay or calcium carbonate. These nanocrystals possess distinctive physico-chemical characteristics which bring out them as a suitable for applications in catalysis, sensing devices, and environmental remediation. The synthesis methods for bio-based nanoparticles vary depending on the type of nanoparticle being produced. Common techniques include solvent evaporation/precipitation methods, emulsion/solvent diffusion methods, coacervation methods, and self-assembly techniques like electrostatic assembly or layer-by-layer deposition [71]. Figure 1 depicts the steps involved in the synthesis of NPs from biobased material.

In conclusion, bio-based nanoparticles offer a sustainable alternative to conventional synthetic NPs due to their eco-friendly nature and potential applications in various fields. The synthesis methods for these particles depend on the nanoparticle type being produced but generally involve extraction or modification processes using natural sources, for instance, animals, plants, or microorganisms [5, 6, 72]. Continued research in this field holds great promise for developing novel nanomaterials with enhanced properties for an extensive range of applications (Fig. 2)

Uptake and translocation of bio-based nanoparticles in plants

Understanding the uptake and translocation mechanisms of bio-based nanoparticles is crucial to assess their impact on plant development. Several studies concluded that these nanoparticles can enter plants through various routes, such as root uptake, foliar application, or seed treatment. As soon as they are within the plant system, they can translocate to different organs via vascular tissues or intercellular spaces [18, 19]. The uptake coupled with translocation mechanisms of bio-based nanoparticles can vary depending on the specific type of nanoparticle and the target organism [73]. However, there are some general mechanisms that can be observed.

Uptake and translocation mechanisms of bio-based nanoparticles

Bio-based nanoparticles can be taken up passively by cells through processes such as diffusion or osmosis. This mechanism is primarily driven by concentration gradients and does not require energy expenditure by the cell. Meanwhile, in active uptake, bio-based nanoparticles can be taken up by cells through specific transporters or receptors on the cell membrane. This mechanism requires poor in the form of adenosine triphosphate and is often selective for certain types of nanoparticles [18]. Once inside the cell, bio-based nanoparticles may undergo intracellular transport to reach their target

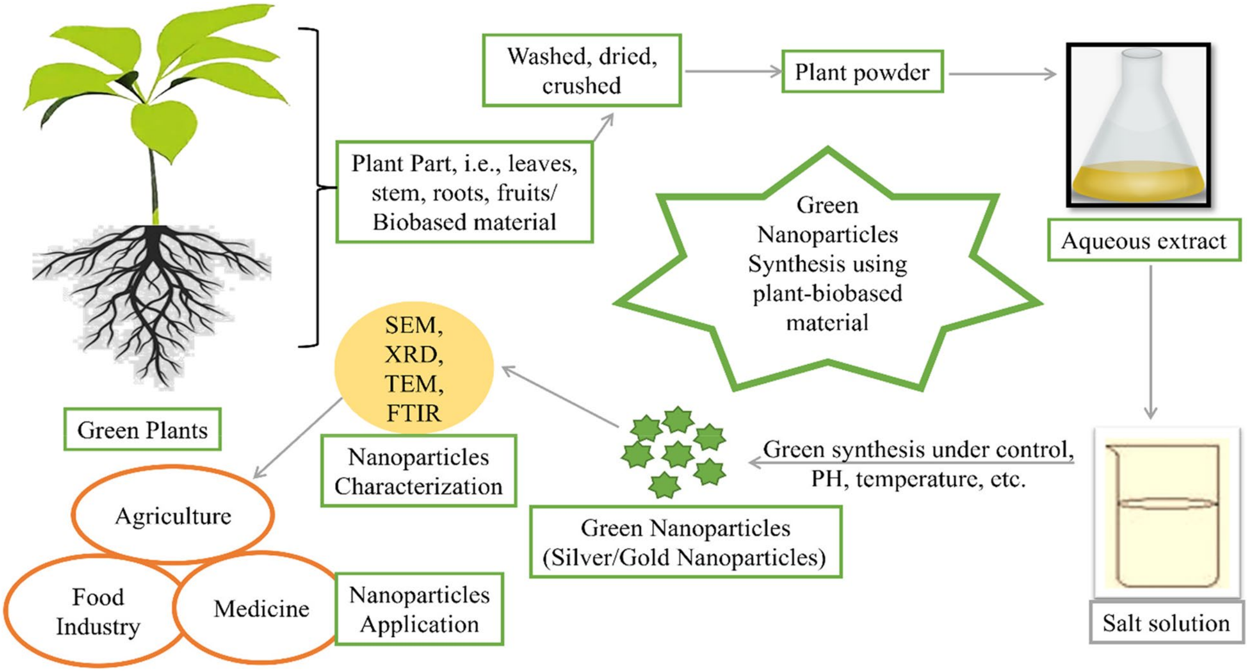


Fig. 1 Pictorial representation for green synthesis of nanoparticles using plant-biobased material

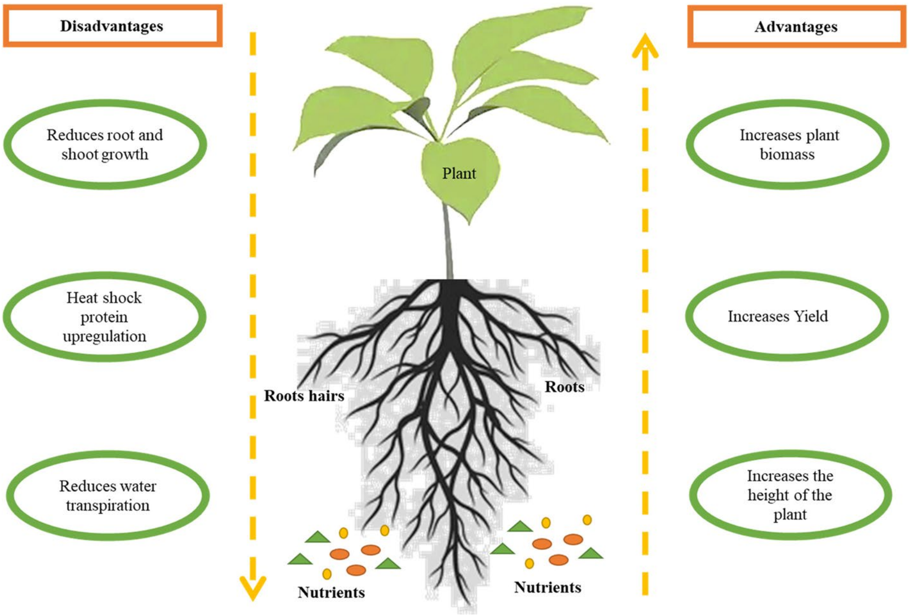


Fig. 2 A diagrammatic representation of how nanoparticles function physiologically in plants

destination. This can involve movement along cytoskeletal elements such as microtubules or actin filaments [73]. Bio-based nanoparticles could be internalized into cells through endocytosis, which involves the formation of vesicles around the particles within the cell membrane. These vesicles then fuse with intracellular compartments such as endosomes or lysosomes. Similarly, exocytosis allows for the release of bio-based nanoparticles from cells [74]. In multicellular organisms, bio-based nanoparticles may be transported through vascular systems such as xylem in plants or blood vessels in animals. This allows for long-distance translocation to several parts of the organism [75].

It's imperative to take note that uptake and translocation mechanisms of bio-based nanoparticles can be influenced by various factors, including nanoparticle size, surface charge, surface functionalization, and interactions with biomolecules present in the surrounding environment [56]. Understanding these mechanisms is crucial for optimizing nanoparticle delivery systems in applications such as drug delivery or plant nutrient uptake enhancement. The bio/geotransformations that take place in the soil influence the toxicity and bioavailability of nanoparticles. When NPs interact with plant roots, they can go to aerial portions and collect in organelles at the subcellular or cellular levels. Plant roots have an important role in the NPs adsorption from the soil, which is regarded as the first step in bioaccumulation. Researchers discovered that root adsorption, as well as changes i.e., crystal phase dissolution, biological transformation, or bioaccumulation, all contributed to the accumulation of NPs in plant tissues. The size of the NPs is important in their absorption since it influences whether they can pass through cell wall pores or plant stomata [76].

Small NPs (3–5 nm) can enter plant roots through different routes, including osmotic pressure, capillary pressures, and direct transit through root epidermal cells. The root epidermal cells contain semipermeable cell membranes with tiny holes, limiting the passage of big NPs. However, some NPs can cause new pores to develop in the epidermal cell wall, making it easier for them to enter. Once inside the root, NPs travel through extracellular gaps until they reach the central vascular cylinder, from which they can ascend through the xylem in a unidirectional fashion. To enter the central vascular cylinder, NPs must penetrate the Casparian strip barrier via symplastic transport [76]. The process begins with binding to a protein carrier on the endodermal membrane of the cell, followed by endocytosis, pore creation, and transport. NPs can travel across cells via plasmodesmata before becoming internalized in the cytoplasm. If NPs cannot be internalized, they accumulate on the Casparian strip. Once in the xylem, NPs are delivered to the shoots before returning to the roots via the phloem [76]. Plants have nanoparticles in their epidermal cell walls, cortical cell cytoplasm, as well as nuclei. NPs that do not penetrate the root surface of soil aggregates can impair nutrient uptake. NPs can also be effectively absorbed in seeds by penetrating the coat via parenchymatic intercellular gaps and diffusing into the cotyledon. Additionally, studying these processes helps ensure safe use and minimize potential adverse effects associated with bio-based nanoparticle exposure (Fig. 3) [75, 77].

Effects of bio-based NPs on plant growth

Bio-based nanoparticles have been reported to influence various aspects of plant growth, including seed germination, root development, shoot growth, leaf morphology, and biomass accumulation [78]. For instance, CNCs have been presented to enhance seed germination rates and promote root elongation in different plant species. Similarly, CSNPs have demonstrated positive effects on shoot growth by enhancing photosynthetic efficiency and nutrient uptake [79, 80]. Bio-based nanoparticles, also known as nano biopesticides or nano fertilizers, have gained significant attention in recent years due to their potential to enhance plant growth and productivity [4]. These nanoparticles are derived from natural sources i.e., plants, fungi, bacteria, and other biological materials. The effects of bio-based nanoparticles on plant growth can be summarized as follows:

Increased nutrient uptake

Bio-based nanoparticles can improve the efficiency of nutrient absorption by plants. Bio-based nanoparticles can play a significant role in increasing nutrient uptake by plants through various mechanisms. Bio-based nanoparticles have a high surface area and can interact with a large number of nutrient molecules, forming strong bonds. This increased adsorption capacity allows the nanoparticles to capture and retain nutrients from the surrounding environment, preventing their loss through leaching or volatilization [81]. Some nutrients, such as phosphorus, are often present in the soil in forms that are not easily soluble and, therefore, not readily available for plant uptake. Bio-based nanoparticles can enhance nutrient solubility by forming complexes with them, increasing their dispersion in the soil solution and making them more accessible to plant roots [82]. Bio-based nanoparticles can promote the growth and development of new roots, increasing the root surface area and enhancing the plant's ability to absorb nutrients from the soil. The nanoparticles can stimulate root elongation and branching, along with root hair formation, which are specialized structures that increase the nutrient absorption capacity of the roots [77].

Bio-based nanoparticles can facilitate the transport of nutrients within the plant, ensuring that they reach the tissues where they are needed most. The nanoparticles can bind to nutrients and transport them, and the plant's vascular tissues are responsible for nutrient transport. This efficient transport system ensures that nutrients are delivered to the actively growing parts of the plant, supporting optimal growth and development [74, 77]. Bio-based nanoparticles can improve the plant's ability to utilize nutrients more efficiently. The nanoparticles can help to stabilize nutrients in the soil, preventing their loss through leaching or volatilization. They can also slow the release of nutrients, ensuring a more sustained supply for the plant over time. This increased nutrient use efficiency reduces the need for excessive fertilizer

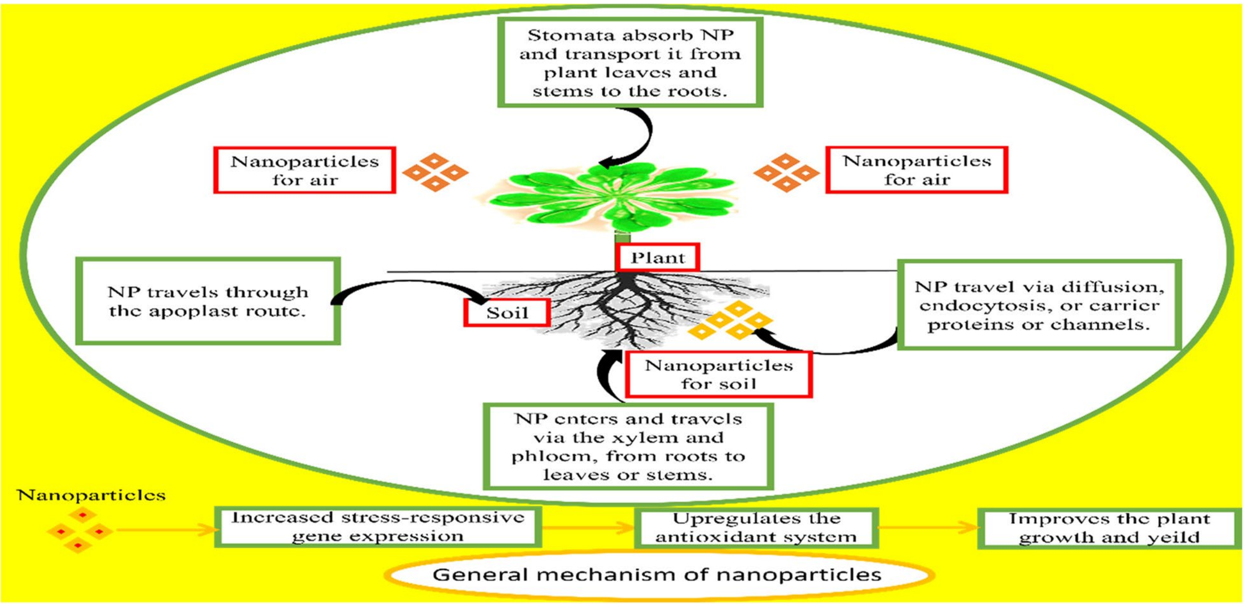


Fig. 3 An organized representation illustrates the mechanisms used by plant species to absorb and transport nanoparticles

applications, minimizing environmental pollution and promoting sustainable agriculture practices [83]. Under stress conditions, for instance, drought, salinity, or nutrient deficiency, plants often experience reduced nutrient uptake and utilization [31]. Bio-based nanoparticles can alleviate these effects by improving nutrient absorption and transport, helping plants maintain their growth and productivity even under adverse conditions. By enhancing nutrient adsorption, solubility, root development, nutrient transport, and nutrient use efficiency, bio-based nanoparticles can significantly increase nutrient uptake by plants, leading to improved growth, productivity, and overall plant health [77, 84].

Enhanced water retention

Bio-based nanoparticles have water retention ability and prevent its evaporation from the soil. This property helps in maintaining optimal soil moisture levels for plant growth, especially in arid or drought-prone regions. Improved water retention also reduces the frequency of irrigation required for crop cultivation [85]. Bio-based nanoparticles can play a significant role in enhancing water retention in various ways. Bio-based nanoparticles have a high surface area and can also absorb and retain a large amount of water. When incorporated into the soil, these nanoparticles can increase the soil's water-holding capacity, allowing it to store more water for plant use [86]. In case of reduced water evaporation, bio-based nanoparticles can form a protective layer on the soil surface, reducing water evaporation from the soil. This layer acts as a physical barrier, preventing water molecules from escaping into the atmosphere [4]. While improving soil structure bio-based nanoparticles can help to improve soil structure by promoting aggregation and reducing compaction. An ill-structured soil with a high porosity allows for better water infiltration and retention. The nanoparticles could fasten soil particles together, creating a more stable structure that resists erosion and maintains soil moisture [87]. In the case of enhanced water uptake by plants, bio-based nanoparticles can enhance water uptake by plants by increasing the surface area of the root and improving root development. The nanoparticles can stimulate the growth of new roots and root hairs, which are specialized structures that increase the plant's ability to absorb water from the soil [77].

By increasing water retention in the soil and enhancing water uptake by plants, bio-based nanoparticles can help to reduce water stress in plants, particularly under drought conditions. Plants treated with bio-based nanoparticles can maintain their water status and continue to grow and produce even when water is scarce [86, 88]. Bio-based nanoparticles enhance the drought tolerance of plants by enhancing their ability to cope with water deficit stress. The nanoparticles facilitate plants in maintaining their water balance, reduce water loss through transpiration, and scavenge ROS (reactive oxygen species) produced under drought conditions [89]. Various nanoparticle examples that help in water retention include lignin NPs that have been used for water retention applications, showing a 1.6 times higher water retention capacity than hydrogel. The size of hydroxyapatite nanoparticles has a strong effect on the kinetics and efficiency of water adsorption. Smaller nanoparticles absorb more water layers, leading to higher water retention capacity. Magnetic nanoparticles, such as magnetite (Fe_3O_4), have been used for water treatment applications, including separation of water pollutants. Nanogels derived from lignin have been used for water retention applications, showing improved water retention capacity compared to hydrogel [88]. These examples demonstrate the potential of various nanoparticles in enhancing water retention, which is valuable for various applications, including agriculture, environmental management, and water treatment.

Increased crop productivity

Bio-based nanoparticles play a substantial role in increasing crop productivity through various mechanisms; bio-based nanoparticles can enhance photosynthesis, the process by which plants convert sunlight into energy. The nanoparticles enhance the light absorption efficiency and utilization by chloroplasts, the organelles responsible for photosynthesis. This increased photosynthetic activity leads to increased biomass production and crop yield [90]. Bio-based nanoparticles have antimicrobial and antifungal properties, which can help to defend plants from diseases and pests. The nanoparticles can inhibit the growth and spread of pathogens, reducing crop losses and improving overall plant health [91]. Bio-based nanoparticles can enhance the plant's ability to tolerate various environmental stresses, including drought, salinity, and nutrient deficiency. Under stress conditions, plants often experience reduced growth and productivity [81]. Bio-based nanoparticles can alleviate these effects by improving nutrient absorption, water retention, and photosynthesis, helping plants maintain their growth and productivity even under adverse conditions [92]. Bio-based nanoparticles can improve seed germination and vigor by enhancing water uptake as well as nutrient absorption by the seeds. The nanoparticles can also protect the seeds from pathogens and environmental stresses, increasing the chances of successful germination coupled with seedling establishment [93]. Bio-based nanoparticles enhance the quality of crops by increasing the nutritional content and reducing the presence of contaminants [94]. Nanoparticles can help increase the levels of vitamins, minerals, and antioxidants in crops, creating more nutrition and benefits for human health [95]. Bio-based nanoparticles offer a promising approach to increasing crop productivity by improving nutrient uptake, water retention, photosynthesis, stress tolerance, and crop quality. By enhancing plant growth and development, bio-based nanoparticles contribute to more sustainable and resilient agricultural practices, helping to meet the growing demand for food production worldwide [91, 93].

Controlled release of agrochemicals

Bio-based nanoparticles could be used as agrochemical delivery systems such as pesticides and herbicides [96]. These nanoparticles can encapsulate the active ingredients and release them gradually over time, ensuring targeted application and minimizing environmental contamination [97]. This controlled release mechanism improves the efficacy of agrochemicals while reducing its adverse impact on non-target organisms [98]. NMs provide a precise and regulated approach for distributing AIs at the correct dosage while reducing AI waste and inadvertent harm to non-target creatures. This technique also decreases the danger of resistance produced by high or low AI concentrations. These nanoscale polymers, including urea–formaldehyde resin, polyurea, or polyurethane, are produced under precise conditions [97]. The scientists used in situ deposition to create a magnetic nanocarrier from diatomite and Fe_3O_4. This nanocarrier successfully contained both cypermethrin (insecticide) as well as glyphosate (herbicide), both of which were then chitosan-coated to restrict their release under an acidic environment. The magnetic characteristics of Fe_3O_4 allowed the separation of nanocarriers from water and soil, allowing for material recycling [97].

Enhanced disease resistance

Bio-based nanoparticles possess antimicrobial properties that can help plants combat various diseases caused by pathogens, for instance, fungi, viruses, and bacteria [99]. These nanoparticles can inhibit the growth as ill as the proliferation of harmful microorganisms, thereby reducing the incidence of plant diseases and improving overall crop health [100]. Bio-based nanoparticles can play a substantial function in enhancing disease resistance in plants through various mechanisms; many bio-based nanoparticles have inherent antimicrobial and antifungal properties, which can directly inhibit the growth and spread of plant pathogens [101]. These nanoparticles can interact with the cell membranes of pathogens, causing damage and preventing their entry into plant tissues. They can also generate ROS coupled with other toxic compounds that can kill or suppress the growth of pathogens [102]. Bio-based nanoparticles can improve the uptake of nutrients by plants, leading to increased plant growth and vigor. Healthy and ill-nourished plants are more resistant to diseases, as they have stronger cell walls and a more robust immune system [74].

Bio-based nanoparticles can stimulate the plant's natural defense responses against pathogens. They can decrease the production of defense-related proteins, such as pathogenesis-related (PR) proteins and phytoalexins, which help to protect the plant from infection [99]. Bio-based nanoparticles could be used as agrochemical carriers, for example, pesticides and fungicides. The nanoparticles can encapsulate and also protect the agrochemicals from degradation and inactivation in the environment [96]. They can also facilitate the targeted delivery of agrochemicals to specific plant tissues or pathogens, reducing the overall amount of chemicals required and minimizing their impact on non-target organisms [100]. Bio-based nanoparticles improve plant's resistance to abiotic stresses, i.e., salinity, drought, and nutrient deficiency [79]. Under stress conditions, plants are more susceptible to disease infection [103]. By alleviating the effects of abiotic stress, bio-based nanoparticles can indirectly enhance the plant's ability to resist diseases [104]. Bio-based nanoparticles develop coatings or films that can be smeared on plant surfaces to reduce the transmission of diseases. These coatings can physically barrier pathogens from entering the plant and can also release antimicrobial substances to inhibit their growth [100]. Bio-based nanoparticles are used in plant breeding programs to develop new crop varieties with enhanced disease resistance [101]. Nanoparticles can be integrated with plant cells or tissues to introduce specific genes or genetic modifications that confer resistance to particular diseases [100]. Overall, bio-based nanoparticles offer a promising approach for enhancing disease resistance in plants by directly inhibiting pathogens, stimulating plant defense responses, improving nutrient uptake, and reducing the abiotic stress impact. By protecting plants from diseases, bio-based nanoparticles contribute to increased crop productivity and sustainability, reducing the need for chemical pesticides and fungicides [99, 101].

Increased photosynthetic efficiency

Bio-based nanoparticles have been found to enhance photosynthesis in plants by increasing chlorophyll content and improving light absorption efficiency [4]. This leads to increased production of carbohydrates as well as energy for plant growth [105]. Bio-based nanoparticles can play a important role in increasing photosynthetic efficiency in plants through various mechanisms. Bio-based nanoparticles can improve the absorption of light energy by plants. Some nanoparticles have optical properties that allow them to scatter and reflect light, increasing the amount of light available for photosynthesis. They can also act as light-harvesting agents, capturing light energy and transferring it to chlorophyll molecules in the chloroplasts [105]. Bio-based nanoparticles can enhance the production and stability of chlorophyll, the green pigment responsible for capturing light energy during photosynthesis. They can also help maintain the structural integrity of chloroplasts, ensuring that the photosynthetic machinery functions optimally [106]. Bio-based nanoparticles can promote the assimilation of carbon dioxide (CO_2) into plant tissues. They can facilitate the transport of CO_2 into the chloroplasts and enhance the enzyme activity riveted in the Calvin cycle, the light-independent reactions of photosynthesis. In the context of photosynthesis, nanoparticles have been reported to play a crucial role in improving the efficiency of this crucial process in plants.

TiO2 nanoparticles have been extensively studied for their potential application in improving photosynthesis in plants. These nanoparticles can act as a photocatalyst, absorbing light energy and transferring it to the chloroplasts of plant cells, thereby enhancing photosynthetic activity. Additionally, TiO_2 nanoparticles can also scavenge ROS generated during photosynthesis, thus protecting the plant from oxidative damage. For example, a study published in the journal Environmental Science and Pollution Research demonstrated that foliar application of TiO2 NPs on maize plants led to an increase in photosynthetic pigments, chlorophyll content, and overall photosynthetic activity. This resulted in improved growth and yield of maize plants. Silver nanoparticles have also been inspected for their potential role in enhancing photosynthesis in plants. These nanoparticles possess antimicrobial properties and can help protect plants from pathogenic infections that may hinder photosynthetic activity. Additionally, silver nanoparticles have been reported to improve the efficiency of light absorption by chloroplasts through their interaction with light energy. A study published in the journal Plant Physiology and Biochemistry reported that foliar application of AgNPs on tomato plants resulted in increased chlorophyll content, stomatal conductance, and net photosynthetic rate. This led to improved growth as well as yield of tomato plants under both normal and stress conditions. Carbon-based nanoparticles such as carbon nanotubes (CNTs) and graphene oxide (GO) have also shown promise for improving photosynthesis in plants. These nanoparticles can act as carriers for delivering nutrients or growth-promoting substances to plant cells, thereby enhancing their metabolic activities, including photosynthesis. For instance, a study published in the journal Nanoscale Research Letters demonstrated that foliar application of multi-walled carbon nanotubes (MWCNTs) on wheat plants led to increased chlorophyll content, stomatal conductance, and net photosynthetic rate. This resulted in improved yield as well as growth of wheat plants under both normal and drought stress conditions. In conclusion, various types of NPs, i.e., titanium dioxide, silver, and carbon-based NPs, have shown potential for improving photosynthesis in plants through different mechanisms such as enhanced light absorption, ROS scavenging, antimicrobial activity, or nutrient delivery. Further studies is needed to fully understand the effects of these NPs on plant physiology and their long-term impact on agricultural productivity and sustainability.

Photorespiration is a process that competes with photosynthesis and reduces its efficiency. Bio-based nanoparticles can inhibit photorespiration by reducing the activity of photorespiratory enzymes and scavenging ROS produced during photorespiration [4]. Bio-based nanoparticles can improve water use efficiency in plants, which is crucial for photosynthesis. They can reduce water loss through transpiration by forming a protective layer on the leaf surface. By maintaining adequate hydration, bio-based nanoparticles help to ensure that the photosynthetic machinery has the necessary water to function efficiently [85]. Bio-based nanoparticles can help safeguard plants from abiotic stresses such as salinity, drought, and nutrient deficiency. Under stress conditions, photosynthesis is often impaired. Bio-based nanoparticles can assuage the effects of these stresses by improving nutrient uptake, water retention, and stress tolerance, indirectly enhancing photosynthetic efficiency [103]. Bio-based NPs can be used to develop novel photosynthetic systems that are more efficient and productive than natural photosynthesis. For example, nanoparticles are used to generate artificial light-harvesting complexes that can capture a broader spectrum of light energy [92]. Overall, bio-based nanoparticles offer a promising approach for increasing photosynthetic efficiency in plants by improving chlorophyll content, light absorption and structure, CO2 assimilation, water use efficiency, and stress tolerance. By enhancing photosynthesis, bio-based nanoparticles can contribute to increased crop productivity and sustainability, helping to meet the growing demand for food production worldwide [105].

Improved stress tolerance

Bio-based nanoparticles can help plants cope with various abiotic stresses i.e., salinity, drought, heat, and heavy metal toxicity (Fig. 4) [104].

Stimulated root development

Bio-based nanoparticles have been displayed to promote root growth by stimulating cell division and elongation

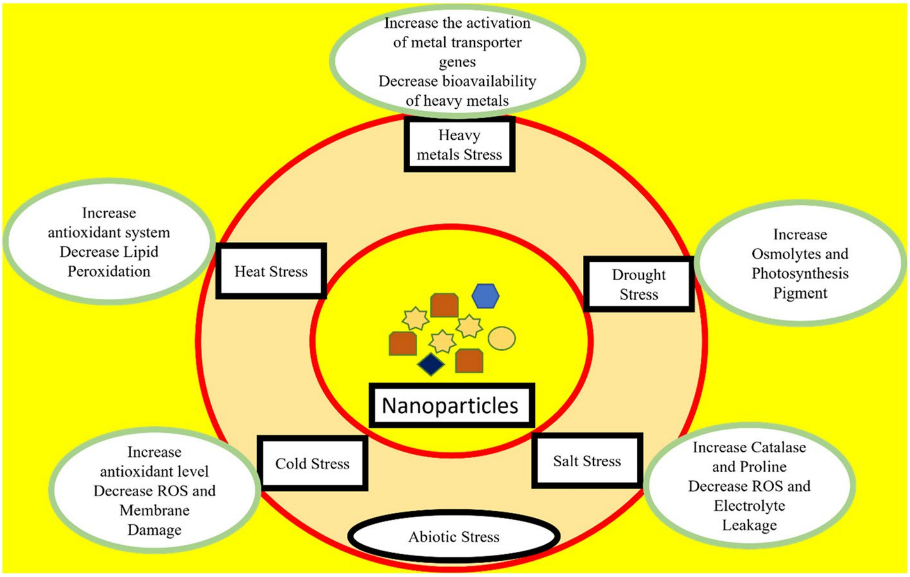


Fig. 4 The systematic diagrammatic representation shows that the involvement of nanoparticles is pivotal in combating abiotic stress

in root tissues. This results in a larger root system with increased surface area for nutrient uptake from the soil [77]. Bio-based nanoparticles can play a significant role in stimulating root development in plants through various mechanisms; bio-based nanoparticles can stimulate root elongation and root branching by influencing the plant's hormonal balance. They can increase the production of auxin, a plant hormone that promotes root growth and root development. This leads to the formation of longer and more branched roots, which enhances the plant's ability to anchor itself in the soil and access water and nutrients [77]. Bio-based nanoparticles can help to improve the overall architecture of the root system. They can promote the development of a more extensive and efficient root system with a higher density of fine roots. This improved root architecture enhances the plant's ability to explore the soil volume and access water and nutrients more effectively [77, 107]. Some of the NPs that have been studied for their role in improved root development include silver nanoparticles, which have been shown to improve root growth and development in plants by promoting cell division and elongation. They also have antibacterial properties, which can protect the roots from pathogens and improve overall plant health. Titanium dioxide nanoparticles have been found to stimulate root growth by increasing the production of ROS in plant cells, which can promote cell proliferation and differentiation. Zinc oxide nanoparticles have been reported to enhance root elongation and biomass accumulation in plants by regulating the expression of genes involved in root development. Carbon-based nanoparticles, i.e., carbon nanotubes and graphene oxide, have also been studied for their potential to improve root development in plants. These nanoparticles can enhance water and nutrient uptake by roots, leading to improved growth and productivity.

Bio-based nanoparticles can influence the interactions between roots and the surrounding rhizosphere, which is the zone of soil influenced by root activity. The nanoparticles can promote the growth and activity of beneficial soil microorganisms, for instance, mycorrhizal fungi and nitrogen-fixing bacteria. These microorganisms can enhance nutrient uptake and root development, leading to improved plant growth [106, 108]. Bio-based nanoparticles are used in plant breeding programs to develop new rootstocks with enhanced root development. Nanoparticles can be incorporated into plant cells or tissues to introduce specific genes or genetic modifications that promote root growth. Overall, bio-based nanoparticles offer promising opportunities for sustainable agriculture by enhancing plant growth, improving nutrient uptake efficiency, increasing stress tolerance, reducing chemical inputs, and minimizing environmental impacts associated with conventional farming practices [87]. However, further research is needed to fully understand their long-term effects on crop productivity and potential risks associated with their use in agricultural systems.

Impact of bio-based nanoparticles on plant differentiation

Plant differentiation refers to the process by which unspecialized cells undergo specific changes to become specialized cells with distinct functions. Bio-based nanoparticles have shown the potential to influence cell differentiation processes such as trichome formation or xylem vessel differentiation [109]. It has been documented that by triggering particular signaling pathways, AuNPs cause the development of trichomes in Arabidopsis leaves. Bio-based nanoparticles (NPs) have emerged as promising tools in agriculture owing to their distinctive properties and potential to enhance plant growth and development [110]. NPs derived from natural sources, i.e., animals, plants, and microorganisms, offer several advantages over synthetic NPs, including biodegradability, biocompatibility, and eco-friendliness [111]. Bio-based NPs can interact with plant cells and modulate gene expression patterns, influencing various developmental processes, including differentiation [112]. NPs can deliver genetic material (e.g., DNA or RNA) into plant cells, leading to the up-or-down-regulation of specific genes involved in differentiation pathways [113].

NPs are widely used in gene expression studies and gene therapy. They can be used to deliver nucleic acids i.e., DNA, RNA, or small interfering RNA (siRNA) into cells to modulate gene expression. For example, lipid-based nanoparticles have been developed for the delivery of siRNA to silence specific genes involved in diseases i.e., cancer and genetic disorders. Gold NPs have also been used to deliver DNA into cells for gene therapy applications. Hormones are signaling molecules that regulate various physiological processes in the body. NPs can be used to mimic hormone signaling by delivering hormone-like molecules to target cells or tissues. For example, polymer-based nanoparticles have been designed to deliver insulin to diabetic patients as a non-invasive alternative to traditional insulin injections. Additionally, lipid-based NPs can be used to deliver hormone replacement therapies for conditions such as menopause. Nanoparticles are ideal for targeted drug delivery due to their small size and ability to encapsulate drugs or therapeutic molecules. They can be functionalized with targeting ligands i.e., antibodies or peptides to specifically bind to receptors on target cells or tissues. For example, liposomal nanoparticles have been developed for the targeted delivery of chemotherapy drugs to cancer cells while minimizing off-target effects on healthy tissues. Similarly, magnetic NPs can be guided by an external magnetic field to target specific sites within the body for drug delivery or imaging purposes.

NPs can interfere with the hormonal balance in plants, affecting differentiation processes. Auxin, cytokinin, gibberellin, and Abscisic acid acts an important role in regulating cell division, organ formation, and tissue differentiation [114]. NPs have the ability to mimic or block these hormones' effects, changing the pathways leading to differentiation [115]. Bio-based NPs can interact with receptors or components of signal transduction pathways, affecting downstream signaling events that regulate differentiation[112]. NPs have the ability to alter cell fate and differentiation patterns by activating or inhibiting particular signaling pathways [116]. NPs can induce or scavenge ROS, which are signaling molecules involved in various cellular processes, including differentiation. NPs have the ability to modify ROS levels, which in turn affects signaling pathways related to differentiation and the redox status of cells [117, 118]. NPs can enhance the uptake as well as transport nutrients into plant cells, providing essential elements for differentiation processes. NPs can act as nutrient carriers, facilitating their delivery to specific tissues or organs where differentiation occurs [83]. Bio-based NPs can enhance plant tolerance to numerous abiotic stresses, like drought, salinity, and nutrient deficiency. Under stress conditions, plants may exhibit altered differentiation patterns to adapt to the changing environment. NPs can assuage the depredation of stress on differentiation by providing protection against stress-induced damage [103].

NPs can interact with plant-associated microorganisms, including beneficial bacteria and fungi, which contribute to the plant growth and development. NPs can modulate the composition and activity of the plant microbiota, indirectly influencing differentiation processes [119]. Bio-based NPs can be engineered to target specific tissues or cell types, enabling the regulated delivery of bioactive molecules or genetic material to regulate differentiation processes. This targeted approach enhances the effectiveness coupled with the specificity of NP applications in plant biotechnology [90, 120]. Bio-based NPs are biodegradable and have a loir environmental impact compared to synthetic NPs. Their use in agriculture reduces the accumulation of persistent NPs in the environment, minimizing potential risks to ecosystems as well as human health [121]. Overall, bio-based nanoparticles offer an engaging methodology for modulating plant differentiation processes. By understanding the mechanisms of interaction between NPs and plants, researchers can design and engineer NPs to control differentiation pathways precisely, leading to improved crop production and enhanced plant traits [122].

Mechanisms underlying the effects of bio-based NPs on plants

The exact mechanisms underlying the effects of bio-based NPs on plants are still not fully understood but are believed to involve complex interactions at the molecular level [123]. These interactions may include nanoparticle-cell membrane interactions indicating changes in membrane permeability or alterations in gene expression patterns through epigenetic modifications [124].

When applied to plants, bio-based nanoparticles have been found to exhibit several beneficial effects, including enhanced growth, improved nutrient uptake, increased stress tolerance, and enhanced disease resistance [125]. Table 3 summaries various nanoparticle examples that play a role in ROS signaling, hormone modulation, and systematic resistance. The underlying mechanisms responsible for these effects can be attributed to several factors.

Bio-based nanoparticles enhance the availability and uptake of essential nutrients by plants. There are several mechanisms that underlie the effects of bio-based nanoparticles on enhanced nutrient availability. These mechanisms include Bio-based NP, such as nanocellulose or chitosan nanoparticles, which have a high volume-to-surface area ratio. This increased surface area allows greater contact with nutrients, facilitating their adsorption and retention. Plants and microorganisms can have greater access to nutrients when the nanoparticles serve as carriers or reservoirs for those nutrients [131]. Bio-based nanoparticles can modify the solubility of nutrients, causing them to be more available for uptake by plants or microorganisms. For example, chitosan nanoparticles can chelate metal ions, increasing their solubility and availability for plant uptake. Similarly, nanocellulose NPs increase the solubility of organic compounds, making them more accessible to microorganisms for nutrient acquisition [132]. Nutrients can be released from bio-based nanoparticles in a regulated manner over time, resulting in a steady supply. This regulated release of nutrients can be accomplished by either encasing the nutrients inside the nanoparticles or by altering the surface characteristics of the NPs to control nutrient release. This sustained nutrient release can improve nutrient uptake efficiency and utilization by plants or microorganisms [97]. Bio-based nanoparticles can provide protection against nutrient losses due to leaching or volatilization. By enclosing nutrients in a protective layer, the nanoparticles can stop them from leaching out of the substrate or soil. This protection can help to retain nutrients in the root zone, increasing their availability for plant uptake or microbial utilization [133].

Bio-based nanoparticles can enhance microbial activity in the rhizosphere or soil, leading to increased nutrient mineralization and availability. The microbes' growth and metabolic activity can be stimulated by the nanoparticles by providing them with a supply of carbon and energy [134]. This increased microbial activity can result in the nutrient release from organic matter or the transformation of complex nutrients into more bioavailable forms [135]. Overall, the mechanisms underlying the effects of bio-based nanoparticles on enhanced nutrient availability are multifaceted and involve chemical, physical, and as ill as biological processes. These mechanisms can vary depending on the specific type of nanoparticles and the targeted nutrient. Bio-based NPs boost the water-holding capacity of soils when applied as soil amendments or incorporated into hydrogels. There are several mechanisms that can explain the effects of bio-based nanoparticles on increased water retention. These mechanisms include bio-based nanoparticles, such as cellulose nanocrystals or chitosan nanoparticles, which have a high volume-to-surface area ratio. This increased surface area allows them to interact with water molecules more effectively, leading to improved water retention [136]. Many bio-based nanoparticles have hydrophilic properties, meaning they have a strong affinity for water molecules. This hydrophilicity allows them to attract and retain water, preventing its evaporation or drainage from the soil [90]. Bio-based nanoparticles can absorb and retain large amounts of water because of their distinctive structure and composition. For example, cellulose nanocrystals have a crystalline structure that can absorb water through capillary action, Although chitosan nanoparticles can create hydrogels that expand when water is present [137].

Bio-based nanoparticles can form stable aggregates or networks in the soil matrix, which can trap and hold water within their structure. These aggregates act as reservoirs for water, slowly releasing it to plant roots over

Table 3 Summarizing various nanoparticle examples that play a role in ROS signaling, hormone modulation, and systematic resistance

Nanoparticle	Role in ROS Signaling	Role in Hormone Modulation	Role in Systemic Resistance	Reference
Lignin Nanoparticles	Enhance photosynthesis and reduce ROS production	Regulate phytohormone signaling	Enhance systemic resistance	[126]
Chitosan Nanoparticles	Enhance photosynthesis and reduce ROS production	Regulate phytohormone signaling	Enhance systemic resistance	[127]
Hydroxyapatite Nanoparticles	Enhance photosynthesis and reduce ROS production	Regulate phytohormone signaling	Enhance systemic resistance	[128, 129]
Magnetic Nanoparticles	Enhance photosynthesis and reduce ROS production	Regulate phytohormone signaling	Enhance systemic resistance	[130]

time. Incorporation of bio-based NPs into the soil can improve its physical properties, such as porosity and aggregate stability. This improved soil structure allows for better infiltration and retention of water, reducing runoff and increasing water availability for plants [121, 138]. Bio-based nanoparticles can create a physical barrier on the soil surface, reducing evaporation rates by limiting direct contact between the soil and air. This barrier prevents moisture loss from the soil surface and helps maintain higher levels of soil moisture [137]. Overall, these mechanisms contribute to increased water retention in soils treated with bio-based nanoparticles, providing benefits for plant growth in addition to drought resistance in agricultural as well as environmental applications.

Regulation of hormone levels

Bio-based nanoparticles modulate the levels of plant hormones such as auxins, cytokines, gibberellins, and Abscisic acid. These hormones act important roles in various physiological processes in plants, including growth regulation, floiring induction, seed germination, and stress responses. Bio-based NPs stimulate plant growth as well as development by altering hormone levels [115]. One mechanism underlying the effects of bio-based nanoparticles on plants is the regulation of hormone levels. Bio-based nanoparticles, such as those derived from plant extracts or microbial sources, can interact with plant cells and tissues, leading to transformations in hormone signaling pathways. Hormones play crucial roles in regulating various aspects of plant growth and development, including seed germination, shoot and root growth, floiring, fruiting, and stress responses. They act as chemical messengers that coordinate different physiological processes in plants [114]. Bio-based nanoparticles can modulate hormone levels by several mechanisms. Firstly, they can directly interact with hormone molecules and alter their stability or activity. For example, bio-based nanoparticles may bind to hormones and protect them from degradation by enzymes or environmental factors. This may lead to increased hormone availability and prolonged signaling effects.

Secondly, bio-based nanoparticles can affect the synthesis or breakdown of hormones within plant cells. Enzymes involved in the manufacture or breakdown of hormones may be stimulated or inhibited by them. Hormone concentration fluctuations may result from this, which may then affect how plants grow and develop [139]. Thirdly, bio-based nanoparticles can influence hormone perception and signaling processes within plant cells. They may interact with hormone receptors or other components of the signaling pathway, either enhancing or inhibiting their activity. This can affect the sensitivity of plants to hormones and modify their responses to internal or external stimuli [116]. Overall, the regulation of hormone levels is a key mechanism by which bio-based nanoparticles exert their effects on plants. By modulating hormone synthesis, degradation, perception, or signaling processes, these nanoparticles can influence various aspects of plant growth and development [115]. Understanding these mechanisms is essential for harnessing the potential benefits of bio-based nanoparticles in agriculture and environmental applications.

Activation of defense mechanisms

It has been documented that plant defense systems against pests and diseases are triggered by bio-based nanoparticles. Bio-based nanoparticles have been shown to activate defense mechanisms in plants, leading to enhanced resistance against various biotic and abiotic stresses. Table 4 states different metallic nanoparticles exhibiting antibacterial activity via a variety of ways.

Several mechanisms have been proposed to explain these effects, including bio-based nanoparticles, which can induce the production of ROS in plant cells. ROS acts as signaling molecules that trigger a cascade of defense responses, including the activation of defense-related genes and antimicrobial compound synthesis. This ROS-mediated signaling pathway plays an important part in plant defense against pathogens [136]. Bio-based nanoparticles can modulate the levels and activities of phytohormones, such as jasmonic acid (JA), salicylic acid (SA), and ethylene (ET). These phytohormones are known to regulate plant defense responses. For example, SA is involved in systemic acquired resistance (SAR) against pathogens, while JA and ET are associated with induced systemic resistance (ISR) [114]. Bio-based NPs boost the production or perception of these phytohormones, leading to the activation of defense mechanisms. Bio-based nanoparticles can induce systemic resistance in plants, where local application of nanoparticles leads to enhanced resistance not only at the site of application but also in distant plant parts. This systemic resistance is mediated by long-distance signaling molecules, such as jasmonates or mobile small RNAs, which activate defense responses in uninfected tissues [100]. PTI is an early immune response triggered by the recognition of pathogen-associated molecular patterns (PAMPs) by pattern recognition receptors (PRRs) on plant cell surfaces. Bio-based nanoparticles can mimic PAMPs or interact with PRRs directly, leading to the activation of PTI and subsequent defense responses [150, 151]. Through a variety of processes, including expanded root surface area, improved root hair production, or altered ion transporters, bio-based nanoparticles can promote plant nutrient uptake. Improved nutrient availability can strengthen plant defenses against pathogens and environmental

Table 4 Different metallic nanoparticles exhibit antibacterial activity via a variety of ways

S. No	Nanoparticles (NPs)	Multiple mechanisms	References
1	NO NPs	NO produces RNOS (reactive nitrogen oxide intermediates) when it reacts with superoxide	[140]
		(a) RNOS damages DNA, generating strand breaks, abasic sites, and Fe depletion in bacterial cells	[141]
		(b) RNOS inhibits microbial respiration by inactivating zinc metalloproteins	[142]
		(c) RNOS induces lipid peroxidation	[143]
2	Chitosan-containing NPs	(a) Because of the positive charge it carries, chitosan binds to DNA in fungal and bacterial cells, blocking mRNA transcription and resulting in protein translation	[144]
		(b) Chitosan reduces the metalloproteins activities	
3	Ag NPs	Silver's antibacterial action is attributed to its Ag + ions	[145, 146]
		(a) Ag + disrupts microorganisms' electron transport chains	
		(b) Ag + binds to DNA and RNA, causing damage	
		(c) Ag + suppresses cell division by preventing DNA replication	
		(d) Ag + ions generate ROS, which are harmful to both bacterial and eukaryotic host cells	
4	ZnO NPs	(a) ZnO NPs damage both lipids and proteins of the membrane, causing cell death	[54, 147]
		(b) ZnO NPs produce Zn2 + ions and ROS, including H_2O_2, which harm the bacterial cell	
5	Cu-containing NPs	(a) Cu interacts with amine & carboxyl groups found in bacteria i.e., *B. subtilis*	[123, 148]
		(b) Higher quantities of Cu^{2+} ions may produce ROS	
6	TiO2 NPs	(a) TiO2 nanoparticles in the photocatalysis process produce ROS, i.e., OH and H_2O_2, when exposed to UVA and near-UV radiation	[128]
7	Mg-containing NPs	(a) ROS generated by MgX2 NPs induce lipid peroxidation in the microbial cell envelope	[149]
		(b) Lipid peroxidation and a decrease in cytoplasmic pH can be induced by MgF2 nanoparticles, resulting in an elevation of membrane potential	

stresses. Overall, the activation of defense mechanisms by bio-based nanoparticles involves complex interactions between nanoparticle properties and plant physiological processes [137, 151]. Understanding these underlying mechanisms is crucial for harnessing the possible advantages of bio-based nanoparticles in agriculture and crop protection strategies.

Antioxidant activity

The effects of bio-based nanoparticles on antioxidant activity can be recognized by several underlying mechanisms. These mechanisms include Bio-based nanoparticles, such as those derived from plant extracts or biopolymers, which possess inherent antioxidant properties. They can scavenge and neutralize ROS, which are extremely reactive molecules that can cause oxidative damage to cells and tissues [118]. By scavenging ROS, bio-based nanoparticles reduce oxidative stress and enhance antioxidant activity. Some bio-based nanoparticles contain functional groups that can chelate metal ions. Metal ions, particularly transition metals like iron and copper, can catalyze ROS production through Fenton and Haber-Iiss reactions. By chelating these metal ions, bio-based nanoparticles prevent their participation in ROS generation, thereby reducing oxidative stress[152]. Bio-based nanoparticles can modulate the activity of antioxidant enzymes i.e., glutathione peroxidase (GPx), superoxide dismutase (SOD), and catalase (CAT) [153]. These enzymes are essential for keeping the redox equilibrium of cells and neutralizing reactive oxygen species. Bio-based nanoparticles can upregulate the expression or enhance the activity of these enzymes, leading to increased antioxidant capacity [154]. Bio-based nanoparticles are often designed to have small sizes and high surface areas, which facilitate their cellular uptake by several mechanisms like endocytosis or passive diffusion [155]. Once inside the cells, these nanoparticles can interact with cellular components involved in antioxidant defense systems, including mitochondria and cytoplasmic antioxidants like glutathione (GSH). Cellular antioxidant activity is increased as a result of this interaction [156].

It has been demonstrated that bio-based nanoparticles can modify a number of signaling pathways connected to antioxidant defense and the oxidative stress response. For example, they can activate nuclear factor erythroid 2-related factor 2 (Nrf2), a TF (transcription factor) that regulates the antioxidant genes expression [116]. Activation of Nrf2 leads to increased synthesis of antioxidant enzymes and molecules, thereby enhancing overall antioxidant activity. Overall, the effects of bio-based nanoparticles on antioxidant activity involve a combination of direct scavenging of ROS, metal chelation, modulation of enzyme activity, cellular uptake and distribution within cells, and modulation of signaling pathways involved in oxidative stress response [117]. These mechanisms collectively contribute to the enhanced antioxidant capacity observed with bio-based nanoparticle treatments.

Nanoparticle-mediated gene expression regulation

The effects of bio-based nanoparticles on nanoparticle-mediated gene expression regulation can be recognized to several underlying mechanisms [113]. These mechanisms involve the interaction between the nanoparticles and cellular components, leading to gene expression changes. Bio-based nanoparticles can be internalized by cells through various uptake mechanisms, such as endocytosis or direct penetration of the cell membrane. Once inside the cells, these nanoparticles can interact with cellular components, including DNA and RNA molecules [155]. After cellular uptake, bio-based nanoparticles can undergo intracellular trafficking within different compartments of the cell, like endosomes or lysosomes. This trafficking process can influence the availability and accessibility of the nanoparticles to their target genes [157].

Bio-based nanoparticles can directly bind to nucleic acids, including DNA or RNA molecules. This binding can affect the stability and structure of nucleic acids, leading to gene expression changes. For example, the binding of bio-based nanoparticles to promoter regions of genes can modulate their transcriptional activity [158]. Bio-based nanoparticles have been reported to induce epigenetic modifications that regulate gene expression [148]. These modifications include DNA methylation or histone modifications, which can alter chromatin structure and accessibility of genes for transcriptional machinery [159]. Bio-based nanoparticles can activate specific signaling pathways within cells, leading to downstream effects on gene expression regulation. For example, activation of the nuclear factor-kappa B (NF-κB) pathway by bio-based nanoparticles has been reported to modulate the pro-inflammatory gene expression [160]. Bio-based nanoparticles can serve as carriers for regulatory molecules such as small interfering RNA (siRNA) or microRNA (miRNA). These regulatory molecules can specifically target and silence or activate specific genes, thereby influencing gene expression [4]. Some bio-based nanoparticles have been reported to generate ROS upon interaction with cells. ROS can act as signaling molecules that regulate gene expression through activation or inhibition of specific transcription factors [118].

Overall, the effects of bio-based nanoparticles on nanoparticle-mediated gene expression regulation are complex and involve multiple mechanisms that depend on nanoparticle properties and cellular context [158]. Understanding these underlying mechanisms is crucial for optimizing nanoparticle design along with application in various biomedical fields, such as drug delivery and gene therapy [161]. It's imperative to note that the mechanisms underlying the effects of bio-based nanoparticles on plants are still being extensively studied and understood; further research is needed for a comprehensive understanding of these mechanisms at molecular levels [79].

Environmental implications and future perspectives

While bio-based nanoparticles offer numerous benefits for plant development and growth enhancement applications, their potential environmental implications need careful consideration. Assessing their long-term impacts on soil health is essential for microbial communities and ecosystem functioning before widespread application in agriculture practices (Table 5) [162].

Environmental implications of bio-based nanoparticles

Bio-based nanoparticles (NPs) are generally biodegradable, breaking down into non-toxic compounds over time. This reduces their persistence in the environment compared to synthetic NPs, curtailing the risk of long-term accumulation and potential adverse effects on ecosystems [6]. Bio-based NPs are often derived from natural sources and exhibit good biocompatibility with plants and other organisms. Their ecotoxicity is generally less than that of synthetic NPs, as it's less likely to induce adverse effects on non-target organisms [163]. Bio-based NPs can interact with soil microorganisms, including bacteria, fungi, and archaea. These interactions can be beneficial or detrimental, depending on the type of NP and the specific microbial community. NPs can influence microbial diversity, activity, and nutrient cycling processes in the soil [164]. While bio-based NPs are biodegradable, there is still a potential for their accumulation in the environment if they are applied in large quantities or if they are not properly managed. Understanding the fate of ill transport of bio-based NPs in different environmental compartments is crucial for assessing their long-term environmental implications [165].

Future perspectives of bio-based nanoparticles

Bio-based NPs can be engineered to release their cargo (e.g., nutrients, pesticides, or genetic material) in a controlled manner, reducing environmental impacts and improving the efficiency of agricultural practices. This precision approach can minimize the use of chemical inputs and reduce the risk of contamination [166, 167]. Bio-based NPs can be functionalized to target specific tissues, organs, or organisms, enabling the targeted delivery of bioactive molecules or genetic material. This approach increases the bio-based NP efficacy in plant protection, nutrient delivery, and bioremediation

Table 5 An overview of the type of NPs that support plant growth and yield [95]

NPs	Plant	Morphology	Concentration	Positive
Ceric dioxide	*A. thaliana*	Quasi-spherical Average particle size-54 nm	200 mg/L	enhanced growth of shoots and roots
Copper	*S. lycopersicum*	Spherical shape 18.18–43.37 nm	100–450 mg/L	Increased lycopene and firmness of the fruit
Silicon	Lentil	Spherical and elongated 14.57–49.88 nm	25 mg/L	Encourage the germination of seeds and biomass
Titanium dioxide	*T. aevum*	Near spheroid, irregular shape Average particle size-41.5 nm	100 mg/L	Increased biomass and lateral root development
Zinc oxide	*M. indica*	hexagonal prism, cuboid, thin rods, irregular shape, near spheroid	100 mg/L	Increased overall yield, i.e., number and sight of fruits per tree
AgNP	*Moringa oleifera* leaves	Rectangular 8–28 nm	30 ppm	Fruit weight
NiONP	*Berberis balochistanica* stem	Rhombohedral agglomerated shape Average size-31.44 nm	31.25 µg/ml	Seedling length Leaf number Shoot length
CuONP	*Camellia sinensis L*	Spherical 50–100 nm	4 µg/ml	Shoot length Fresh weight Dry weight
AgNP	*Berberis lycium*	Spherical 10–100 nm	60 ppm	Shoot length Fresh weight Seeds per pod
CuNP	*Mentha longifolia*	Spherical Average size-23 nm	50 mg/L + 5 ml/day	Root length

applications [168]. Developing cost-effective and scalable methods in terms of the synthesis of bio-based NPs is crucial for their widespread adoption in agriculture. Green synthesis approaches using renewable resources and environmentally friendly processes can reduce the environmental footprint of NP production [169]. Establishing regulatory frameworks and standards for the production, application, and disposal of bio-based NPs is necessary to guarantee their responsible and safe application in agriculture. This includes guidelines for environmental risk assessment, monitoring, and end-of-life management [170]. Integrating bio-based NPs with sustainable agriculture practices, such as organic farming and precision agriculture, can maximize their benefits while minimizing potential risks. This holistic approach considers the entire agricultural system and aims toward boosting crop productivity, reducing environmental impacts, and promoting soil health [50]. To fully comprehend how bio-based NPs interact with plants, soil microbes, and the environment, more research is required. This includes studying the long-term effects of NPs on soil health, biodiversity, and ecosystem functioning. Innovation in NP design, functionalization, and application methods will further enhance their potential in sustainable agriculture [171].

By addressing these environmental implications and exploring future perspectives, bio-based nanoparticles can be harnessed to revolutionize agriculture while minimizing their environmental impact and promoting sustainable practices [172]. Although nanoparticles' efficiency in overcoming abiotic stress is well-proven, almost all of these studies have been conducted in the laboratory. Concerns have been expressed about the increasing use of nanoparticles, specifically their possible harmful influence on the ecosystem and the buildup of NPs in parts of plants that are edible. As a result, it is critical to perform targeted research to create acceptable evaluation procedures for analyzing the impact of NPs as well as nano-fertilizers on the abiotic and biotic elements of ecosystems. Apart from this the plant parts and nanoparticles derived from these plant can also be used to treat various human infection [173–180].

Conclusion

Bio-based nanoparticles (NPs) have emerged as a promising tool in agriculture, providing an eco-friendly and sustainable approach to enhance plant development, growth, and differentiation. With their unique properties such as biodegradability, biocompatibility, and targeted delivery, bio-based NPs have valuable applications in plant biotechnology. They can influence gene expression, hormonal signaling, and signal transduction pathways, thereby regulating differentiation processes and improving root development, shoot proliferation, and flower and fruit production. Additionally, bio-based NPs enhance nutrient uptake and transport, supplying essential elements for plant growth. Furthermore, they improve plant tolerance to abiotic stresses like drought, salinity, and nutrient deficiency by mitigating the negative effects on differentiation and other physiological processes. Compared to synthetic NPs, bio-based NPs offer advantages such as decreased environmental accumulation, reduced toxicity, and better compatibility with plant cells, minimizing adverse effects on plant growth. As research progresses, bio-based NPs hold immense potential for transforming agriculture by contributing to sustainable crop production, improved plant traits, and enhanced resilience to environmental stresses. To ensure their safe and effective use, further exploration of interaction mechanisms, optimization of NP design and application methods, and the establishment of regulatory frameworks are necessary.

In summary, bio-based nanoparticles offer a sustainable and promising approach to enhance plant development, growth, and differentiation, contributing to the advancement of agriculture and food security in a changing global environment. Furthermore, it is critical to examine the effects of NPs on the health of humans and set acceptable limits. Future research should focus on the production of low-cost, non-toxic, environmentally friendly, as well as self-degradable nanoparticles to help commercialize nanotechnology in the farming industry.

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Authors' contributions

S.K.V wrote the main manuscript text, and D.S. prepared figures and tables, reviewed the manuscript, and made the necessary changes; P.K., A.M. and R.K. made and helped in revision.

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Declarations

Ethics approval and consent to participate

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Competing interests

The authors declare no competing interests.

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