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REVIEW

Potentiality of metal nanoparticles in precision and sustainable crop production

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Abstract

Nanotechnology is a novel technique that has potential applications in multiple sectors and can easily transform the conventional farming system into modern agriculture in an eco-friendly, sustainable way. It is the modern farming strategy that can fulfill the higher demand for foods among the world's population along with overcoming the inherent limitations in traditional agriculture like soil disturbance, imbalance in biodiversity, and environmental risk. Metal nanoparticles (NPs) are used as nano-pesticides, nano-fertilizers, nano-sensors, and nano-priming agents that can be synthesized through physical, chemical, or biological methods. They also help to mitigate issues such as high production costs, excessive pesticide and fertilizer requirements, soil depletion, and various biotic and abiotic challenges. Additionally, agroecosystems can achieve enhanced nutrient utilization efficiency, more efficient pest control, and less environmental impact with the application of metal NPs. Nanoencapsulation allows chemical pesticides and fertilizers to be precisely dosed by deliberately releasing their ingredients incrementally. Metal NPs, used as biosensors and seed-priming materials, can be integrated with precision agriculture to enable precise resource management. Aside from that, they can contribute to seed germination even in adverse conditions. A variety of important information from different research findings on metal NPs, their characteristics, synthesis process, and their roles in precision and sustainable agriculture are included in this article. This article also covers future perspectives for metal NPs based on these impacts. This study discusses the benefits of metal NPs on plant growth and development, as well as their effects on precision agriculture for crop production.

Keywords: nanotechnology, metal nanoparticles, precision and sustainable agriculture, potentiality of nanoparticles

Introduction

The number of people in the world is constantly growing, and these restlessly growing people's desire for food is equally increasing (Van Dijk *et al*., 2021). According to the United Nations, there will be 8.5 million people on the planet by 2030, and food production will need to rise by almost 50% in order to feed everyone (Mittal *et al*., 2020). Besides, the use of fertilizers and pesticides excessively, the deterioration of soil fertility and health, the reduction of irrigation water availability, and the low yield of crops are some of the major issues that the authorities in charge of food security and global agriculture are confronting (Shahzad *et al*., 2019). Additionally, farmers have long used traditional methods, which have limited agricultural output due to increased fertilizer consumption, environmental contamination, microorganism-causing diseases, and abiotic stressors (Jayaraman *et al*., 2021). Ultimately, these cause an increase in the production costs, reduction in biodiversity and resources (Barros-Rodríguez *et al*., 2021; Onana, 2022). So, this increasing worldwide need for food, along with the urgent issues of resource shortage and environmental deterioration, calls for creative approaches to agriculture (Garcia and Alamanos, 2022; Al-juthery *et al*., 2023). Therefore, two important tactics to address these issues are sustainable agriculture, which puts an emphasis on environmental stewardship, and precision agriculture, which uses data to maximize resource efficiency (Shukla *et al*., 2024). In order to improve productivity, strengthen farmer economies, and promote a pollution-free, environmentally friendly environment, the agricultural crop production industry has to transition to more contemporary technology (Zain *et al*., 2023).

In this case, nanotechnology is a novel strategy which can contribute to precision and sustainable agriculture (Hofmann *et al*., 2020; Nazir *et al*., 2020; Usman *et al*., 2020; Zhang *et al*., 2021; Behl *et al*., 2022). NPs are employed in many domains due to their tiny size, high surface area, and compatibility with flexible substrates (Wu *et al*., 2020a; Goyal *et al*., 2023). These unique features of

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NPs can mitigate the shortcomings of conventional farming (Kumar *et al*., 2021; Maluin *et al*., 2021; Singh *et al*., 2021). In recent times, metal NPs have emerged as a very promising instrument in agriculture, offering plant growth promotion, improved crop productivity, food security, improved pest/disease management, antifungal activities, and reduced pesticide use (Bahrulolum *et al*., 2021; Cruz-Luna *et al*., 2021; Shende *et al*., 2021; Maity *et al*., 2022). Therefore, using NPs presents a compelling substitute for traditional breeding (Ioannou *et al*., 2020; El-Saadony *et al*., 2021) and can revolutionize contemporary farming methods (Mittal *et al*., 2020; Behl *et al*., 2022). For example, metal NPs-based sensors (nano-sensors) can enable real-time monitoring of nutrient levels, insect infestations, and soil conditions, enabling accurate and timely treatments (Kumar *et al*., 2020; Yadav *et al*., 2023). In addition, the slow or controlled release of fertilizers, nano-herbicides, and nano-fungicides that decrease soil toxicity, increase nutrient efficiency, and lessen overdosing-related adverse effects is all made possible by the use of metal NPs (Fincheira *et al*., 2023; Singh *et al*., 2023). Furthermore, metal NPs are also employed in agriculture to boost yields while maximizing output, minimizing nutrient losses, minimizing production expenses, and reducing the number of products needed for plant protection (Usman *et al*., 2020). Thus, metal NPs can contribute to precision farming, which will drive the next green revolution by monitoring environmental parameters and taking targeted steps to increase output (economic yield) while minimizing input (pesticides, fertilizers, herbicides, etc.) (Panpatte *et al*., 2016; Zavala-Yoe *et al*., 2017; Finger *et al*., 2019).

Precision agriculture helps to ensure the sustainability of primary production by improving crop management, decreasing waste, and lowering expenses (Monteiro *et al*., 2021). Increased crop yield and less environmental impact may result from using nanotechnology in agriculture to improve the efficiency of agricultural inputs (Singh *et al*., 2021). In heavy metal-stressed conditions, NPs may promote plant growth, which supports sustainable agriculture and the phytoremediation of polluted soil (Faizan *et al*., 2023). Furthermore, using metal NPs in agriculture may effectively suppress phytopathogenic fungi (Cruz-Luna *et al*., 2021). Top-down and bottom-up are the two main synthesis approaches used to create nanomaterials (Tripathy *et al*., 2023). Biological organisms are used in green synthesis of NPs, which is more economical and environmentally benign than physical and chemical synthesis (Altammar, 2023). Because, the physical and chemical methods used to create NPs are complex, costly, and antiquated; they also generate hazardous waste that is harmful to the environment and human health (Khan *et al*., 2019a). With potential uses as antibacterial agents, nano-pesticides, and fertilizers, biosynthesized metal oxide NPs have great potential for sustainable crop production, management, and protection (Maity *et al*., 2022).

This study investigates the potential of metal NPs to transform sustainable and precision agriculture. It addresses metal NPs, their synthesis method, and their advantageous role in enhancing precision agricultural crop production. It discusses their potential applications in sensing, controlled-release systems, and environmental remediation. By understanding the benefits and challenges associated with metal NPs, this study seeks to offer significant insights for decision-makers, researchers, and agricultural practitioners who wish to apply nanotechnology to solve the pressing issues of environmental sustainability and food security.

Review methodology

A systematic and extensive literature review was conducted to understand the use of metal nanoparticles in precision and sustainable agriculture. The following databases were searched: Google Scholar, ScienceDirect, SpringerLink, and PubMed (the keyword search terms were: metal nanoparticles, nanotechnology in agriculture, nano-fertilizers, nano-pesticides, seed nano-priming, precision agriculture, sustainable crop production). The search was mainly targeted at peer-reviewed articles published within the era of 2010–2024, and especially targeted at literatures whose research was conducted after 2018. The reference lists of identified relevant articles were screened manually in order to locate more pertinent studies and cover the topic exhaustively. Moreover, recently published different articles and specialist meetings were utilized in order to monitor the development of trends and unpublished research findings.

Commonly used metal NPs

The field of science and engineering that studies materials with dimensions of one-hundredth of a nanometer or less is known as nanotechnology (Mody *et al*., 2010), and there are two categories for this large class of nanomaterials: metallic and non-metallic NPs (Yih and Al-Fandi, 2006). Metal-based NPs commonly generated and used include cerium oxide, gold, zinc oxide, copper oxide/dioxide, silver, and titanium dioxide (Rico *et al*., 2015). Besides, iron, magnesium, and cobalt are also used (Kumari and Chauhan, 2019; Sharma *et al*., 2022; Vijayanandan and Balakrishnan, 2018). NPs are the most commonly used conventional farming method because of their small size, high efficiency, ease of handling, portability, and long shelf life (Hazarika *et al*., 2022). Moreover, they have many beneficiary effects on plant growth and development as long as crop production, even, in case of any biotic or abiotic stress (Fig. 1 and Table 1).

IRON OXIDE NPs (FeO NPs)

Hematite (α-Fe_2O_3), magnetite (Fe_3O_4), and maghemite (γ-Fe_2O_3) are the most frequent types of iron oxides in nature, and for biomedical applications, the first two are the best option (Ali *et al*., 2016). Spherical-shaped FeNPs are extracted from different plant species, and their size ranges from 0 to 150 nm (Abegunde *et al*., 2020).

TITANIUM DIOXIDE NPs (TiO_2 NPs)

There are two types of TiO_2 based on structure: rutile and anatase (Chen and Mao, 2007). TiO_2 NPs boost the plant's immunity rate, which raises crop output by 30% (Waghmode *et al*., 2019). Plants can benefit from its application in nano form to increase production and growth (Faraz *et al*., 2020).

SILVER NPs (Ag NPs)

The most prevalent metallic NPs with antibacterial properties are silver NPs. Spherical-shaped (1–100 nm) particles are extracted from different plant species like *Acalypha indica*, *Allium cepa*, *Allium sativum, Annona squamosa,* etc. (Rajan *et al*., 2015). Besides, they are slender, round, oval, and triangular, shaped like a flower (Zhang *et al*., 2016), and their biological impacts are influenced by their coatings' surface charges, which can impact their interaction with living systems (Powers *et al*., 2011).

ZINC OXIDE NPs (ZnO NPs)

Zinc (Zn), a mineral essential to plant development and production, contains a component needed at modest levels for enzyme and protein functions (Al Jabri *et al*., 2022). Zn NPs can take many forms, including rods, plates, spheres, boxes, hexagons, tripods, tetrapods, wires, tubes, rings, cages, and even flowers (Siddiqi *et al*., 2018).

MAGNESIUM OXIDE NPs (MgO NPs)

Because of their exceptional physicochemical properties, which include outstanding corrosion resistance, low electrical and high thermal conductivity, exceptional refractive index, physical strength, etc., magnesium NPs (MgO) are environmentally friendly, commercially viable, and industrially significant NPs, and their different shapes (spherical, cubic, nano-flower, rod-like, cluster, hexagonal, etc.) are seen during green synthesis (Abinaya *et al*., 2021).

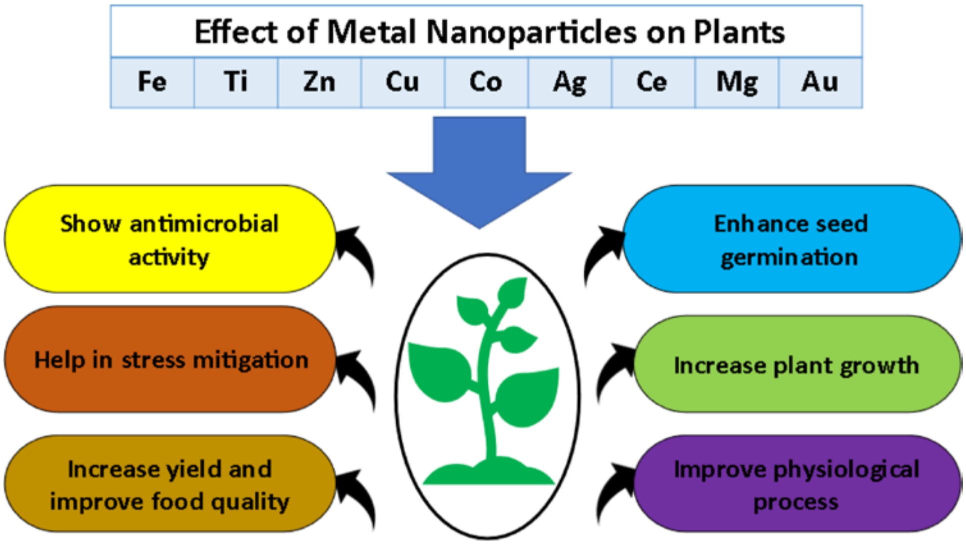

Fig. 1. Beneficiary effects of metal NPs on plant.

COBALT OXIDE NPs (CoO NPs)

The magnetic characteristics of cobalt oxide NPs make them useful in a wide variety of technological applications, such as catalysts, energy storage devices, electrochemistry, sensors, magnetic fluids, and biomedicine (Ogunyemi *et al*., 2023).

COPPER OXIDE NPs (CuO NPs)

Variable microelectrode potential, renewable surface area, and a high surface-to-volume ratio make copper NPs popular catalysts (Din and Rehan, 2017). Copper NPs (Cuprous oxide and cupric oxide) that include agrochemicals such as herbicides and fertilizers are being used more often in agriculture as substitutes for their traditional forms (Bakshi and Kumar, 2021).

CERIUM OXIDE NPs (CeO_2 NPs)

A member of the lanthanide group, Cerium is the most prevalent rare metal with catalytic capabilities (Singh *et al*., 2020a). Cerium NPs sized 5–30 nm can be extracted from plant species like *Acalypha indica, Olea europaea, Hibiscus Sabdariffa,* etc.

GOLD NPs (Au NPs)

Gold NPs can be synthesized from leaves of *Brassica juncea, Aegle marmelos, Aloe vera, Coriandrum sativum, Euphorbia hirta,* etc., and roots of *Zingiber officinale, Morinda citrifolia, Angelica archangelica,* etc. SPR phenomenon causes gold NPs to absorb strongly in the visible spectrum, with a maximum in the 500–600 nm range (Husen, 2017). They have the properties of high mobility and solubility, high adsorption capacity, high reactivity, and catalytic capacity (Venzhik *et al*., 2021).

Synthesis methods of metal NPs

Nanoparticle synthesis can be carried out utilizing either top-down or bottom-up logic (Raliya *et al*., 2017). The top-down strategy involves the processing of bulk materials into NPs using techniques such as milling, grinding, sputtering, thermal/laser ablation, and so on (Ndaba *et al*., 2022). This approach's drawback is its limited ability to manage nanoparticle size and increased number of contaminants (Zulfiqar *et al*., 2019). By building NPs from small entities through reduction and oxidation processes, the bottom-up approach produces NPs with fewer flaws (Singh *et al*., 2015). These two approaches include chemical, physical, and biological synthesis methods (Fig. 2). However, the stability and monodispersion of the nanoparticle size are two issues with the chemical and physical procedures, despite the fact that they are generally simple to perform (Kaningini *et al*., 2022). Methods usually used for metal nanoparticle synthesis are described in Table 2.

PHYSICAL METHOD OF SYNTHESIS

There are specific impacts of using NPs in agriculture. The process used to synthesize NPs is the primary contributing factor. Physical synthesis requires high temperatures and several hazardous materials. Alterations to the synthesis process, such as catalysts and temperature reductions, could make NPs safer to use. This will lead to a synthesis approach that is both cost-effective and environmentally safe. This led to research on reducing the use of hazardous substances and replacing them with natural molecules, which gave rise to the "green chemistry" movement (Quaresma *et al*., 2009).

Some common methods of physical synthesis from Table 2 are described briefly:

Evaporation-condensation

The two most crucial physical procedures, evaporation-condensation and laser ablation, guarantee that the NPs are distributed evenly and that the thin films that are produced are free of solvent contamination (Iravani *et al*., 2014). The initial method for creating nanocrystalline metals and alloys was gas condensation. Thermal evaporation sources, such as electron beam evaporation devices or joule-heated refractory crucibles, can evaporate inorganic or metallic materials within a pressure range of 1 to 50 mbar (Rajput N., 2015).

Laser ablation

The process known as "laser ablation" involves focusing a concentrated laser beam—an acronym for "light amplification by stimulated emission of radiation"—on a specific region of a solid surface with the goal of vaporizing any material that absorbs the light (Kim *et al*., 2017). Using this technology, different forms of nanomaterials and nanostructures have been developed with higher chemical, electrical, optical, and magnetic capabilities (Larosi *et al*., 2022). Metal NPs like TiO_2, Au, Fe_2O_3, Ag, etc. can be generated by the laser ablation approach (Kim *et al*., 2017).

Pulsed laser deposition

Pulsed laser deposition is another type of physical vapor deposition. In this manner, the material to be deposited is targeted by the pulsed, high-power laser beam. After vaporizing off the target in a plasma plume, this material condenses into a thin layer on a

Table 1. Metal NPs and their beneficiary applications/functions on different crops and performance against stress conditions.

Name of metal NPs	Method of synthesis	Applications/functions	References
FeO NPs	• Physical • Chemical • Biological (Zúñiga-Miranda *et al*., 2023)	1. Wheat grain's protein content was found to be elevated after application to the leaves.	Bakhtiari *et al*. (2015)
		2. At low concentrations, plant cellular growth increased.	Yuan *et al*. (2018)
		3. Respiration, redox reactions, chlorophyll synthesis, and leghemoglobin production in nodules are facilitated by the presence of iron.	Singh *et al*. (2021)
		4. Enhanced the amount of protein, lipid, oleic, and linoleic acid of *Glycine max.*	Sheykhbaglou *et al*. (2018)
		5. Application of iron oxide increased plant height, branch count, leaf area, stem diameter, and biomass of moringa plant.	Tawfik *et al*. (2021)
		6. Chlorophyll content was boosted in peanut plants.	Rui *et al*. (2016)
		7. Can improve wheat seed germination and seedling growth.	Alam *et al*. (2015)
TiO_2 NPs	• Physical • Chemical • Biological (Alabdallah *et al*., 2024)	1. Provided antibacterial, biocompatible, and biodegradable qualities in addition to photochemical, mechanical, and physical stability in several agricultural contexts.	Rodríguez-González *et al*. (2019)
		2. Enhanced plant dry weight, lengthen leaves, and ameliorate soil salinity of broad bean.	Santás-Miguel *et al*. (2023)
		3. When given in small amounts through the roots or leaves, it can enhance the performance of crops by enhancing photosynthesis, raising the activity of certain enzymes, and boosting chlorophyll content.	Singh *et al*. (2019)
		4. When applied topically (5 mgL^{-1}), enhanced the activity of RuBisCO and phosphoenolpyruvate carboxylase, two antioxidant enzymes, as well as the pigment levels in chickpea during cold stress.	Silva *et al*. (2022)
		5. When treated to tomato (nano-anatase with 16 nm; 0.1, 0.2, and 0.05 gL^{-1}) under heat stress, it boosted stomatal opening and increased photosynthesis.	Qi *et al*. (2013)
		6. Canola seedling development and seed germination rate were both improved by application at a concentration of 2000 mgL^{-1} and particle size of around 20 nm.	Shende *et al*. (2021)
ZnO NPs	• Physical • Chemical • Biological (Naveed Ul Haq *et al*., 2017)	1. Antibacterial agent against harmful microbes, such as fungi, *Escherichia coli*, and *Staphylococcus aureus.*	Sabir *et al*. (2014)
		2. Supported development and heightened stress marker activity (SOD, proline) of sunflower in saline environments.	Subbaiah *et al*. (2016)
		3. Improved seedling survival, higher chlorophyll content, earlier blooming, and accelerated germination of peanut.	Prasad *et al*. (2012)
		4. Enhanced growth and elevated antioxidant activity (SOD, MDA) at a concentration of 1.9 mgL^{-1} in case of tomato.	Singh *et al*. (2016)
		5. All-zinc oxide irrigation increased corn's growth, leaf dry weight, and leaf area.	Taheri *et al*. (2016)
		6. The antibacterial ability was assessed against many types of plant diseases caused by fungal strains, Gram-positive, and Gram-negative bacteria.	Keerthana *et al*. (2021)
		7. In pearl millet, there was increased activity of plant defense enzymes, including lipoxygenase, phenylalanine, and polyphenol oxidase.	Nandhini *et al*. (2019)
Ag NPs	• Physical • Chemical • Biological (Iravani *et al*., 2014)	1. In drought-stressed conditions, administered at a concentration of 10 μgmL^{-1} were observed to increase lentil seed germination.	Hojjat and Ganjali (2016)
		2. Administration of AgNPs improved salinity tolerance in *S. hortensis* seedlings and activated plant defense mechanisms against salt toxicity.	Nejatzadeh (2021)

Continued

Table 1. Continued.

Name of metal NPs	Method of synthesis	Applications/functions	References
		3. Foliar treatment at 20, 40, and 60 mgL^{-1} boosted the fenugreek plant's growth parameters, such as shoot length, number of leaves/plants, and shoot dry weight.	Khan *et al*. (2023a)
		4. When treated with 6 μgmL^{-1} of AgNPs, there were significant increases in fresh and dry weights and an incitement to the production of secondary metabolites of wheat plants.	Khan *et al*. (2023b)
		5. At 75 ppm exhibited 75% mortality and are effective against pests and beetles.	Alif Alisha and Thangapandiyan (2019)
		6. Influence the bacterial populations in soil used for agriculture, which can positively or negatively impact plants and the ecosystem.	Panyala *et al*. (2008)
		7. Antifungal activity was observed against *Fusarium oxysporum, Rhizoctonia solani, and Curvularia sp.*	Balashanmugam *et al*. (2016)
		8. Relative viral concentrations and tomato plant disease severity were both lowered by 50 ppm treatment.	Noha *et al*. (2018)
		9. Compared to generic antibiotics, AgNPs exhibited stronger antibacterial action against *Erwinia cartovora.*	Kale *et al*. (2021)
		10. AgNPs were synthesized using the aqueous leaf extract of *Aloysia citrodora*, and their antifungal and anti-oomycete activity against *Macrophomina phaseolina, Pythium aphanidermatum, F. oxysporum, Botrytis cinerea,* and *Paecillomyces formosus* was assessed.	Hassanisaadi *et al*. (2022a)
MgO NPs	• Physical (Hornak, 2021) • Chemical (Daisy *et al*., 2015) • Biological (Abinaya *et al*., 2021)	1. Showed exceptional antimicrobial activity at a very low dose (250 μgmL^{-1}) against *R. solanacearum*.	Cai *et al*. (2018)
		2. Showed better photosynthetic ability, enhanced nutritional absorption, reduced lipid peroxidation, and enhanced antioxidant capacity of soybean.	Faizan *et al*. (2022)
		3. Under arsenic stress, magnesium oxide improved the morpho-physiological characteristics of rice plants.	Ahmed *et al*. (2021a)
		4. Has the potential to be employed in the control of plant pathogenic bacteria *R. solanacearum* and the root-knot nematode *M. incognita*.	Khan *et al*. (2022a)
		5. 30% to 50% improvements in yield of maize were observed, and the grains' nutritional content was positively impacted	Segatto *et al*. (2023)
		6. A notable antibacterial impact was noted against the rice pathogen A. oryzae.	Ahmed *et al*. (2021b)
CoO NPs	• Physical • Chemical • Biological (Huang *et al*., 2021)	1. Cobalt nanoparticle-infused barley seeds boost production without having any harmful effects.	Seregina *et al*. (2021)
		2. Cobalt NPs measuring 11.4 nm are absorbed by the barley plant's roots and boost plant biomass.	Tombuloglu *et al*. (2021)
		3. An efficient rice leaf blight pathogen-fighting nano-pesticide and growth enhancer for Arabidopsis plants.	Ogunyemi *et al*. (2023)
		4. Cucumber plantlet growth and development can be regulated by cobalt NPs at concentrations between 0.1 and 10 gh^{-1}.	Polischuk *et al*. (2018)
		5. Low concentrations (50 and 100 mgL^{-1}) induced photosynthesis and growth of rapeseed.	Jahani *et al*. (2020)
CuO NPs	• Physical • Chemical • Biological (Pourmadadi *et al*., 2024)	1. (a) Efficient within the size range of 11–14 nm in combating *Phytophthora infestans* on tomato. (b) In case of soybean and chickpea, increased germination up to the dose of 2000 ppm copper, but growth of roots was hindered beyond the dose of 500 ppm copper.	Kasana *et al*. (2016)

Continued

Table 1. Continued.

Name of metal NPs	Method of synthesis	Applications/functions	References
		2. The antifungal efficacy was investigated against *Fusarium oxysporum* and *Alternaria solani* which fungi are harmful to tomato.	Vinod Saharan *et al.* (2015)
		3. Plant species like coffee, tea, cocoa, banana, and citrus, and others are also protected from significant fruit and leaf diseases caused by fungi including blight, powdery or downy mildew, and rust.	Rai *et al.* (2018)
		4. Act as antimicrobial agent and protect plant from oxidative stress and iron deficiency.	Shobha *et al.* (2014)
		5. At various concentrations reduced the effect of the cotton leaf worm on cotton plants.	Muhammad *et al.* (2016)
		6. Enhanced stomatal conductance and photosynthesis rate of *Capsicum annuum.*	Rawat *et al.* (2018)
CeO_2 NPs	• Physical • Chemical • Biological (Nosrati *et al.*, 2023)	1. Administering doses of 0, 125, 250, and 500 $mgkg^{-1}$ resulted in improved grain yield, more biomass in the shoots, and improved plant growth of wheat.	Rico *et al.* (2014)
		2. Improved fruit output, tomato plant growth, and radish antioxidant capacity at 20 ± 1.9 nm and 8 ± 1 nm sizes, respectively.	Prakash *et al.* (2021)
		3. The addition of CeO_2 NPs enhanced the physiological reactions of Brassica.	Rossi *et al.* (2016)
		4. At the foliar dose of 10 mgL^{-1} reduced oxidative damage caused by drought in sorghum and boosted photosynthesis and grain yield.	Djanaguiraman *et al.* (2018)
Au NPs	• Physical • Chemical • Biological (Khan *et al.*, 2022b)	1. Provided strong antiviral and antibacterial effects.	Khan *et al.* (2024)
		2. Early phases of development and germination may be favorably impacted by nano-priming.	Hong *et al.* (2021)
		3. Applying foliar spray directly to leaves facilitates effective nitrogen delivery and reduces stress.	Nile *et al.* (2022)
		4. Keep the state of nutrients intact, stop losses after farming, and lessen abiotic stressors.	Wahid *et al.* (2022)

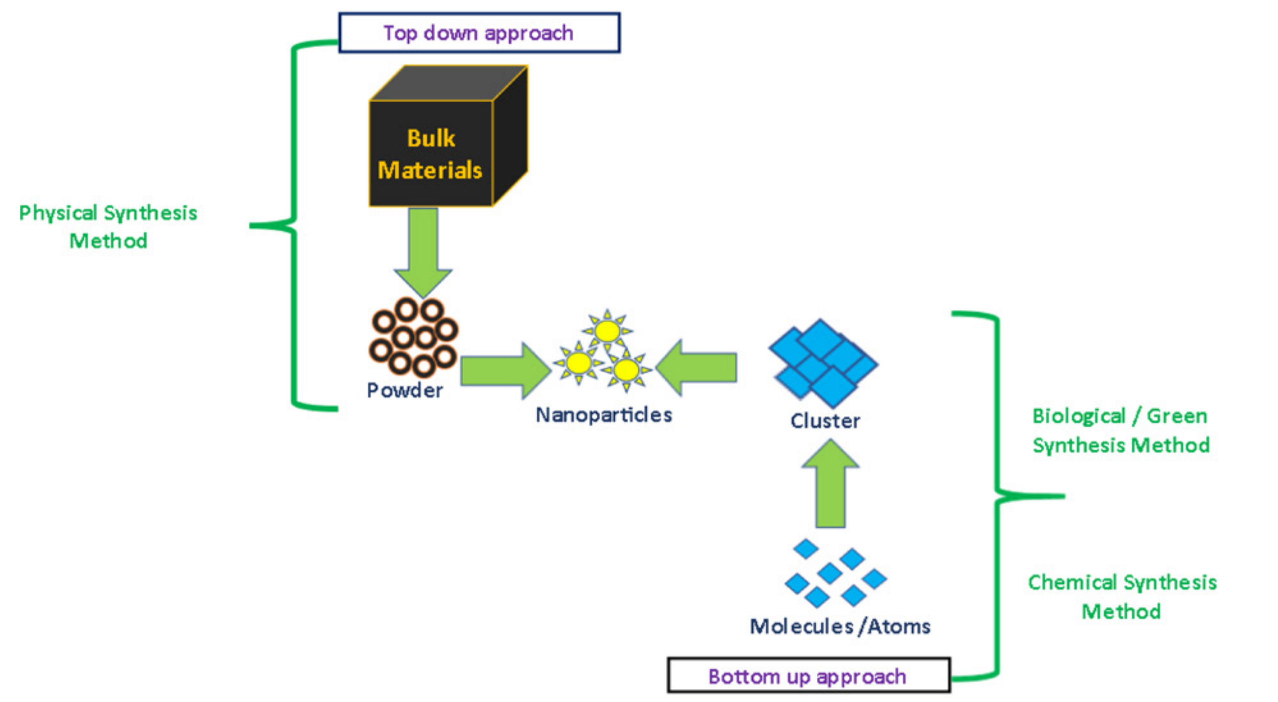

Fig. 2. Physical, chemical and biological synthesis approaches for metal NPs.

Table 2. Different synthesis approaches of metal NPs along with their merits and demerits.

Approaches	Method of synthesis	Name of methods	Merits	Demerits
Top-down approach	Physical synthesis method	• Mechanical grinding • Arc discharge • Thermal/laser ablation • Laser pyrolysis • Ultrasonication • Sputtering • Vapor phase synthesis • Radiolysis • Ion implantation • Electro exploitation • Inert gas condensation • Pulsed laser deposition • Evaporation condensation • Flash spray pyrolysis • Etching (Chemical)	- No harmful chemicals are used. - Rapid speed. - Maintained purity. - Uniformity in dimensions and form. - Beneficial for extensive production with improved properties. - New properties that are improved lead to more properties that are enhanced. - The characteristics of NPs are mutable. - Formation in liquid media without the use of surfactant. - Adaptable method for creating ionic NPs.	- High expense, radiation exposure, and productivity. - Demand a lot of pressure, heat, and energy. - High dilution - Challenging form and size tunability. - Variable forms. - Produced large amount of impurities. - Reduced stability. - Modified surface chemistry, and physicochemical characteristics of NPs are among the factors contributing to the mass production of trash. - Ablation rate reduction - Unwanted contamination. - Very sensitive microstructure that can be ground.
Bottom-up approach	Chemical synthesis method	• Sol-gel process • Irradiation • Chemical vapor deposition • Atomic condensation • Sonochemical method • Hydrothermal • Atomic condensation • Chemical precipitation • Electrolysis • Chemical reduction • Plasma-enhanced chemical vapor deposition • Flame and spray pyrolysis • Microwave technique • Photoreduction • Ultrasound • Supercritical fluid precipitation • Solvothermal • Spinning • Aerosol-based process	- Simple to use. - Elevated yield. - Reduced impurities. - Economical. - High adaptability in terms of surface chemistry. - Stability in temperature. - Controllability of size. - Diminished dispersity. - Regulated surface morphology. - Generate high-quality NPs.	- The possible dangers to human health and the environment from the use of hazardous chemicals and organic solvents. - Reduced purity. - It is necessary to chemically purify the NPs. - Challenging large-scale manufacturing. - Costly approach. - Produce a small amount of material - Multicomponent deposition presents challenges. - Restricted repeatability.
	Biological/green synthesis method	• Microbes (Fungi, virus, bacteria, yeast) • Plants • Algae	- Nanoparticle size is regulated and less harmful. - Utilization of compounds with lower toxicity. - Consistent NPs. - Energy savings. - Great output. - Super cheap. - Consistent results. - Created a rather homogeneous particle. - Firmly adhere to the substrate (Major advantage).	- Gradual synthesis process. - Comperatively more costly - Production is increased by heating conditions.

Source: Jamkhande *et al*. (2019); Iravani (2011); Kaningini *et al*. (2022); Ndaba *et al*. (2022).

substrate, like a silicon wafer that faces the target. This might occur with a background gas (oxygen, for example), which is commonly employed to deposit oxides and fully oxygenate the films being formed, or it could occur in a completely vacuum environment (Haider *et al*., 2022).

Thermal decomposition and ball milling

Thermal decomposition is the term for the endothermic chemical breakdown brought on by heat, which causes the molecule's chemical bond to disintegrate (Masoud *et al*., 2008). The breakdown of metal at a particular temperature produces the NPs. Ball milling is the most basic and inexpensive mechanical technique for transferring kinetic energy from the grinding media to the material being reduced. For instance, ZnO, CuO, Ti, and Ag are produced by this process (Ijaz *et al*., 2020).

Sputtering

During the sputtering process, a powerful gas or gaseous plasma ion bombardment is applied to the target material. This action ejects small particles from the atomic or molecular element's surface. Sputtering occurs via momentum exchange between the element atoms and ions. Sputtering allows for the deposit of films that have the same composition as the target source. It is a flexible method that works with nearly every kind of material (Rane *et al*., 2018).

Ultrasonication

The other method used was the ultrasonication of the ultrasonic sound wave frequency in the range of >20 kHz. It was applied to the solution to awaken the homogeneous dispersion as it causes an upset of the intermolecular force, decreasing the cluster formation of NPs into the base fluid (Mahbubul *et al*., 2017).

Inert gas condensation

Inert gas condensation is the process by which metal or inorganic material is evaporated from an evaporating source in the presence of an atmosphere of inert gas and subsequently condensed on a very cold substrate for a substantially shorter amount of time, resulting in the formation of NPs.

Pyrolysis

In contrast to that, pyrolysis is the process that is used to atomize the liquid solution containing the metal composite that is present. The carrier gas transports the atomized droplets to a furnace. The solvent undergoes a chemical dissociation in the furnace after the solution has been heated to the proper temperature. When the process is being done, then the solution will always get more and more saturated, and there will be no solvent left after some time of heating.

CHEMICAL METHOD OF SYNTHESIS

The chemical method of synthesis is a bottom-up approach that produces NPs in a liquid medium with various reactants present. Low temperatures are present when the reactions take place. The primary benefit of this process, aside from toxicity, is that it produces NPs at low temperatures, which saves manufacturing time and costs while maintaining the desired particle size. Here are some commonly used chemical synthesis techniques discussed:

Chemical reduction

A major contributing element to the success of the wet chemical synthesis approach is the kinetic and thermodynamic provisions that allow composition, shape, and size to be adjusted to reflect changes in surface, electrical, and optical properties (Nikam *et al*., 2018). Chemical reduction is an effective wet chemical procedure for generating zero-valent NPs from chemically reduced aqueous metal salts, such as silver nitrate, in the case of Ag NP manufacture (Nam and Luong, 2019). Reducing agents like citrate, borohydride, etc., are used to feed electrons to metal ions that reduce metal salt to become zero-valent. A stabilizing ingredient, such as sodium citrate in the case of silver NPs production, stabilizes reduced NPs (Aashritha, 2013).

Sol-gel technique

The sol-gel approach is a more chemical way of generating diverse nanostructures, particularly metal oxide NPs. In this method, the molecular precursor (usually metal alkaline compounds) is allowed to dissolve in either alcohol or water and converted into gel by warming and mixing through hydrolysis. This technique has a great influence over both the surface and texture features of the materials (Parashar *et al*., 2020). This technique involves a range of processes, comprising particle formation, hydrolysis of the precursors, agglomeration, particle formation, and condensation (Rajput, 2015).

Co-precipitation

Co-precipitation is the sequential precipitation of multiple products from a solution. It is the most economical and useful way to prepare NPs. In this process, metal hydroxide is precipitated from a salt precursor in a solvent in the presence of a base.

Chemical vapor deposition

Chemical vapor deposition is the chemical reaction that takes place on or near a heated substrate surface. Consequently, a vapor deposits a solid material in the shape of a single crystal, thin film, or powder (Carlsson and Martin, 2010). NPs with distinct characteristics are created by altering the temperature of the substrate, the material's composition, and the experimental setup.

Flame spray pyrolysis

This could be altered via flame spray pyrolysis, which can be utilized to create nearly all elemental multicomponent NPs from solvents and affordable solid and liquid precursors. Currently, functionalized cobalt NPs and carbon black are produced industrially via flame spray pyrolysis (Grohn *et al*., 2014). Since a lot of less volatile raw materials dissolve in organic solvents in addition to water, the best strategy might be to inject liquid precursors straight into the flame. This is due to the ease of handling and administering liquid precursors. One such material is zinc oxide, which can be manufactured using this method (Wallace *et al*., 2013).

Spinning

Spinning is an alternative method for producing NPs, mostly used for TiO_2 (Mohammadi *et al*., 2014). A spinning disc reactor with a controllable temperature system is used to synthesize NPs. A rotating disk is incorporated into the reactor's design to exclude oxygen and halt unintended chemical reactions. In order to stop undesirable reactions, this disk is frequently filled with nitrogen or inert gas. The disc rotates at various rates while the liquid water and the precursor are pushed in (Ealia and Saravanakumar, 2017).

BIOLOGICAL/GREEN METHOD OF SYNTHESIS

The biological synthesis of NPs begins with the mixing of precursors of noble metal salts with biomaterials. A variety of resources, such as microbes (fungi, yeasts, algae, viruses, bacteria) and other plant components, can be utilized for this process (Fig. 3) (Dikshit *et al*., 2021). There are two types of this synthesis process, namely Biosorption (metal ions adhere to the living thing) and Bioreduction (chemical reduction of metal ions via biological methods), and many factors influence the choice of biological synthesis technique for NPs (Karnwal *et al*., 2024). Metal NPs like Ag are synthesized by the bioreduction method from the bacteria Klebsiella pneumonia (Kalimuthu *et al*., 2008), and Cu is synthesized from the bacteria Bacillus sphaericus JG-A12 by both biosorption and reduction methods (Das *et al*., 2014). Nanoparticle formation is initiated by combining biomaterials with precursors of noble metal salts (Sriramulu *et al*., 2021). Alkaloids, polyphenols, proteins, reducing sugars, and flavonoids are examples of biomaterials that serve as capping and reducing agents for forming NPs from their metal salt precursors (Kuppusamy *et al*., 2016). Metal NPs from plants are synthesized by combining plant extract with metal salt, and in this case, any type of plant part, like a stem, leaf, flower, root, fruit, or even seed, can be used (Shafey, 2020) (Fig. 2). There are three ways in which plant-mediated synthesis of NPs may be accomplished: (i) intracellularly (inside the plant), (ii) extracellularly (using extracts from plants), and (iii) using particular phytochemicals and a number of plants possess the capacity to gather metals and then transform them into NPs within their cells (Dikshit *et al*., 2021). Biological applications, including biomineralization, bioremediation, bioleaching, and biocorrosion, have historically benefited from the interaction between metals and microbes (Klaus-Joerger *et al*., 2001). As a consequence of the oxidation or reduction of metallic ions by biomolecules produced by microbial cells, such as enzymes, proteins, carbohydrates, and polysaccharides, NPs are created during the process of microbial synthesis (Prabhu and Poulose, 2012). Synthesis of metal NPs from bacteria and fungi was done by mixing bacterial culture with metal salt solution and keeping fungal hyphae in metal ion solution, respectively (Singh *et al*., 2020b) (Fig. 3). Metal NPs synthesized from biological sources (fungi, bacteria, plants) are shown in Table 3.

As the sources for synthesis are easily available, the great advantage of green synthesis is that it takes less time and energy to prepare than physical or chemical methods (Bhardwaj *et al*., 2020).

Migration and mode of action of metal nanoparticles in plants

Metal nanoparticles migrate into plants through various anatomical pathways. Plant's external structures and internal vascular and

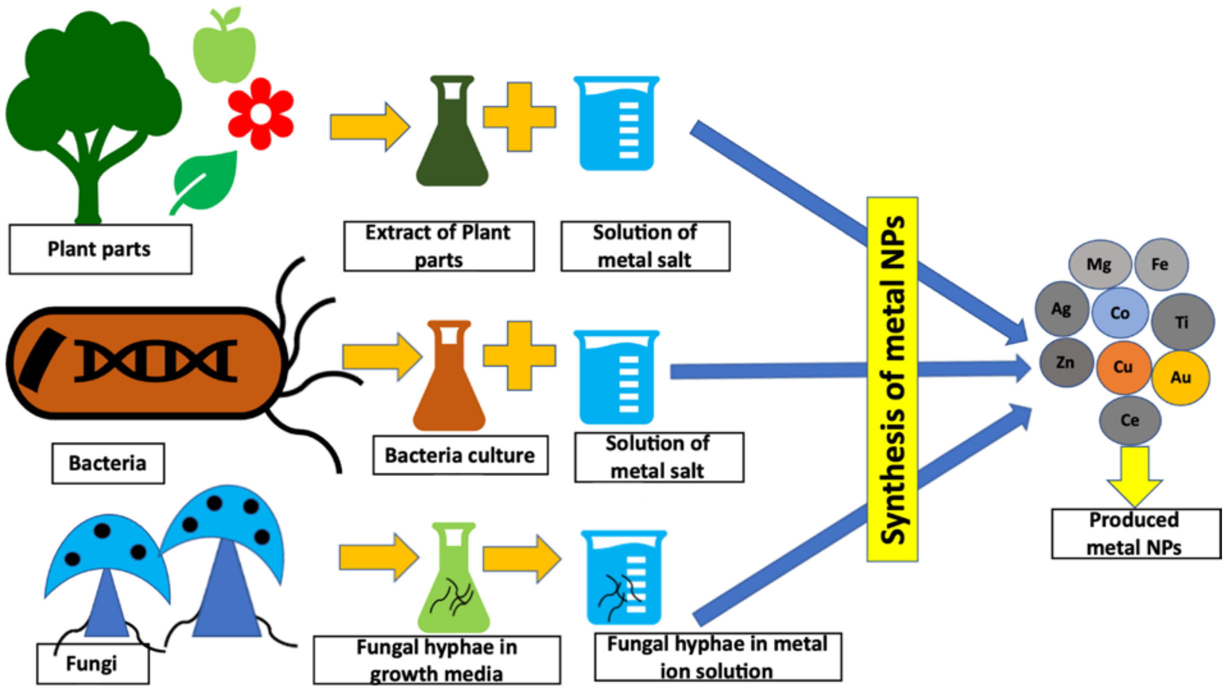

Fig. 3. Green synthesis process of metal NPs.

cellular systems work together to facilitate translocation of these particles and their initial uptake (Avellan *et al.*, 2019).

Metal NPs function uniquely within plants by connecting to cellular elements to change biological processes that boost plant growth and stress protection (Francis *et al.*, 2024). Nanoparticles enter cells through roots and leaves due to their tiny dimensions and extensive surface area (Zhu *et al.*, 2022). Nanoparticles that contact the root epidermis enter plant tissue by passing through either apoplastic or symplastic pathways which leads to xylem transport through the transpiration stream or they can be absorbed through leaf stomata or disrupted cuticular layers (Nawaz *et al.*, 2023) (Fig. 4). The delivery of nucleic acids into plant cells occurs through tissue infiltration using advanced nanocarriers like ZIF-8 nanoparticles which belong to the metal organic frameworks (MOFs) category (Yu *et al.*, 2024). The interaction between plant cell walls and membranes and nanoparticles depends on their physical properties, including size and morphology as well as surface charge (Ďúranová *et al.*, 2024).

MNs trigger diverse physiological effects when they enter plants to provide stress protection while delivering nutrients. The application of titanium dioxide (TiO_2) nanoparticles in plants functions through upregulating transcription factors, including WRKY and catalase genes, which results in environmental stress mitigation (Farahi *et al.*, 2023). The application of silver nanoparticles (AgNPs) stimulates seed germination along with providing salt stress protection through their action on antioxidants leading to increased root development along with better plant growth in saline environments (Bsoul *et al.*, 2023). The dual functionality of zinc oxide (ZnO) nanoparticles consists of supplying required zinc micronutrients Zn2+ for enzyme cofactor function together with regulating cellular osmotic conditions in abiotic stress conditions (Thounaojam *et al.*, 2021). Besides, ZnO nanoparticles reduce heavy metal toxicity alongside other abiotic challenges through improved water efficiency and stronger antioxidant system operation (Umair Hassan *et al.*, 2024). Furthermore, green-synthesized ZnO nanoparticles possess detoxification potential to help plants fight against pathogenic stresses (Velsankar *et al.*, 2022).

The flow of MNPs through a plant's vascular system enables these particles to affect different parts of the plant body (Siddiqi and Husen, 2017). Following absorption, the nanoparticles move through both the phloem and the xylem, which permits their distant tissue influence (Ma *et al.*, 2017). The potent use of MNPs for plant improvement relies on nanoparticle profile as well as synthesis procedure and solution concentration, which synergistically optimize plant defense mechanisms alongside yield benefits through integrated delivery pathways and genetic regulation (Jiang *et al.*, 2022).

Impacts of the MNs on plants

SUPPLY PLANTS WITH NUTRIENTS

Metal NPs reduce nutrient loss, which improves nutrient uptake, nutrient efficiency, and crop yield through utilizing NPs as nano-fertilizers in agriculture. The chemical fertilizer requirement is decreased day by day using metal NPs. NPs have a long-term effect on the ecosystem and agricultural soil health (Kumar *et al.*, 2022). Various application methods of nano-fertilizer are observed, including soil application, foliar application, seed treatment, and hydroponics.

Soil Application is a popular method, and it plays a crucial role in enhancing crop production. Physical, chemical, and biological factors like soil compaction, stability, pH, soil microbes, etc., must be considered at the time of nano-fertilizer application in soil (Javed *et al.*, 2022). In poor weather and soil conditions, foliar application may be utilized. Additionally, this method reduces nutrient loss and promotes nutrients to enter the plant system directly. It shows higher nutrient efficiency (Mahil and Kumar, 2019). ZnO nano-fertilizer was reported to enhance plant growth, antioxidants, and photosynthetic pigments in maize (Azam *et al.*, 2022). According to Salcido-Martinez *et al.*, (2020), the highest levels of biomass and photosynthetic pigments in green beans were seen in foliar application of Mg NPs (Table 4). Seed priming shows a greater improvement in germination and other growth parameters in pearl millet by using ZnO NPs (Kumar *et al.*, 2024). Through seed priming, ZnO NPs also increased the percentage of germination in

Table 3. Metal NPs and some of their recently found biological source of synthesis.

Name of metal NPs	Synthesized from	Size	References
Ag NPs	Fungi: • *Ganoderma lucidum* • *Piriformospora indica* • *Penicillium oxalicum*	 • 15–22 nm • 1–30 nm • 25–67 nm	Aziz *et al*. (2019); Aygün *et al*. (2020); Feroze *et al*. (2020)
	Bacteria: • *Streptomyces olivaceus* (MSU3) • *Lactobacillus paracasei* • *Bacillus subtilis*	 • 12–20 nm • 8–26 nm • 3–20 nm	Gomaa (2019); Sanjivkumar *et al*. (2019); Alsamhary (2020)
	Plant: • *Prosopis farcta* (fruit) • *Tropaeolum majus L.* • *Piper longum L.* • *Holoptelea integrifolia* • *Camellia sinensis* • *Allium cepa var. aggregatum* • *Cannabis sativa* • *Descurainia sophia*	 • 11–15 nm • 38–82 nm • 28.8 nm • 32–38 nm • 4–50 nm • 27–43 nm • 26.52 nm • 1–35 nm	Khatami *et al*. (2016); Hassanisaadi and Shahidi Bonjar (2017); Kumar *et al*. (2019); Rolim *et al*. (2019); Salari *et al*. (2019); Valsalam *et al*. (2019); Yadav *et al*. (2019); Chouhan and Guleria (2020); Shanmugam *et al*. (2022)
ZnO NPs	Fungi: • *Aspergillus niger* • *Fusarium keratoplasticum*	 • 8–38 nm • 8–38 nm	Mohamed *et al*. (2019)
	Bacteria: • *Bacillus haynesii* • *Pseudomonas putida*	 • 20–100 nm • 20–46 nm	Jayabalan *et al*. (2019); Rehman *et al*. (2019)
	Plant: • *Punica granatum* • *Tecoma castanifolia* • *Trianthema portulacastrum* • *Rheum turketanicum*	 • 32.98–81.84 nm • 70–75 nm • 25–90 nm • 17–20 nm	Khan *et al*. (2019b); Nemati *et al*. (2019); Sharmila *et al*. (2019); Sukri *et al*. (2019)
TiO_2 NPs	Fungi: • *Aspergillus flavus*	 • 12–15 nm	Raliya *et al*. (2015)
	Plant: • *Citrus sinensis* • *Artocarpus heterophyllus* • *Musa alinsanaya*	 • 20–50 nm • 15–20 nm • 31.5 nm	Hameed *et al*. (2019); Amanulla and Sundaram (2019); Ullah *et al*. (2019)
FeO NPs	Bacteria • *Streptomyces* spp.	 • 65–86 nm	Rajeswaran *et al*. (2020)
	Plant: • *Ruellia tuberosa* • *Platanus orientalis* • *Moringa oleifera*	 • 20–80 nm • 38 nm • 15–21 nm	Devi *et al*. (2019); Vasantharaj *et al*. (2019a); Aisida *et al*. (2020)
CuO NPs	Plant: • *Moringa oleifera* • *Ruellia tuberosa* • *Ocimum tenuiflorum*	 • 35–95 nm • 83.23 nm • 20–30 nm	Dabhane (2019); Joshi and Prakash (2019); Vasantharaj *et al*. (2019b)
Au NPs	Fungi: • *Fusarium solani* • *Thermoascus thermophilus* • *Trichoderma hamatum*	 • 40–45 nm • ~10 nm • 5–30 nm	Abdel-Kareem and Zohri (2018); Molnár *et al*. (2018); Clarance *et al*. (2020)
	Bacteria: • *Lactobacillus casei* • *Deinococcus radiodurans* • *Bacillus cereus*	 • 7–56 nm • 43.75 nm • 40–50 nm	Kikuchi *et al*. (2016); Li *et al*. (2016); Pourali *et al*. (2017)
	Plant: • *Anacardium occidentale* • *Citrus maxima* • *Pistacia atlantica* • *Radix Ranunculi Ternati* • *Piper betle*	 • 10–60 nm • 27–30 nm • 50–60 nm • 9–24 nm • 15–55 nm	Ren *et al*. (2012); Yu *et al*. (2016); Hamelian *et al*. (2018); Sunderam *et al*. (2019); Patra *et al*. (2020); Hassanisaadi *et al*. (2021)

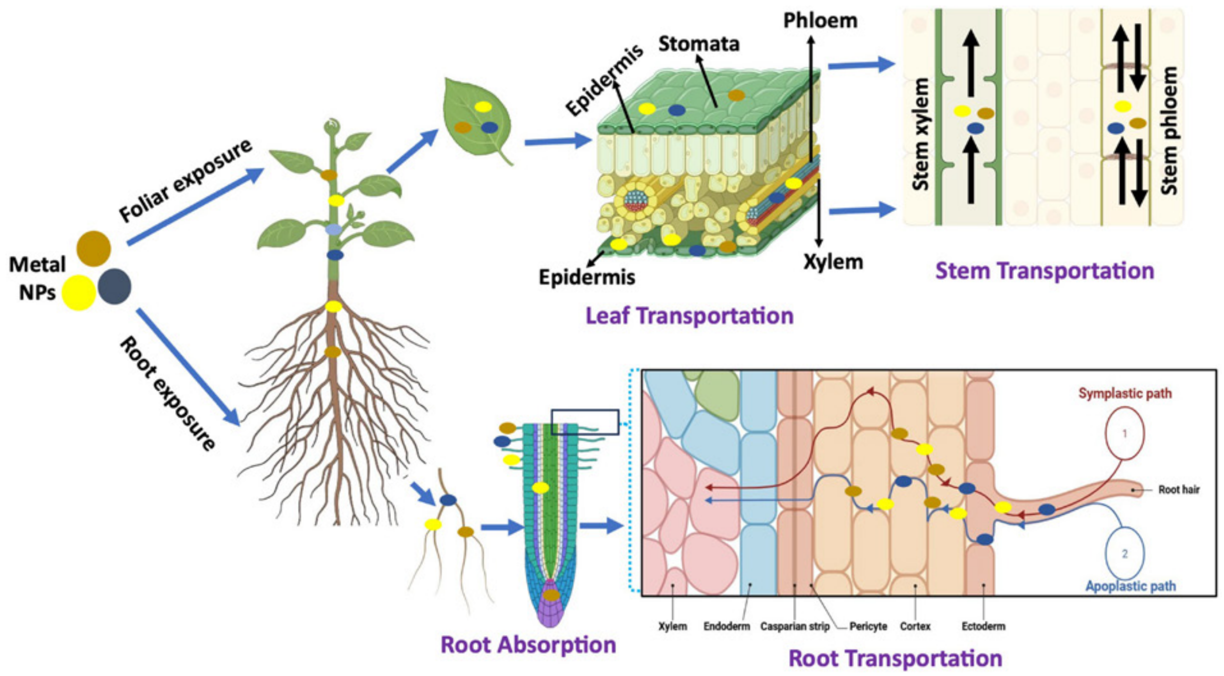

Fig. 4. Absorption and transportation pathway of metal nanoparticles into plant.

Table 4. Benefits of using NPs for enhancing the nutrient supply to plant.

NPs	Crop	Method of application	Effect	References
Ni	Bean	foliar	Ni content increased, whereas Mn, Fe, Cu, and Zn levels decreased. Showed positive effects on physiological characteristics.	Qadir and Fathulla (2024)
ZnO	Potato	-	Increased the tuber quality and Zn content but reduced the total number of potato tuber.	Zhang *et al*. (2024)
Mn (MnO_2 and Mn_3O_4)	Radish	-	Vitamin C and sugar content increased. However, elements like Cu, Fe, Mg, Zn, Na, and K were suppressed.	Zhao *et al*. (2024)
Fe + Si	Bean	Seed priming	Increased K intake and enhanced the antioxidant defense mechanism.	Koleva *et al*. (2022)
Fe_3O_4	Moringa	foliar	Showed positive impact on the photosynthetic pigment, antioxidant enzyme nutrient content of N, P, K.	Tawfik *et al*. (2021)
TiO_2	Lettuce	-	Enhanced the biomass of the roots and shoots, but significantly reduced the amount of nutrients and inhibited the uptake of water and nutrients.	Hu *et al*. (2020)
Mg	Green Bean	foliar	Increased the biomass and photosynthetic pigment	Salcido-Martinez *et al*. (2020)
Mn	Wheat	foliar	Enhanced the amount of Mn in grain, shoot, and root but reduced the amount of nitrate-N in soil.	Dimkpa *et al*. (2018)
TiO_2	Maize	hydroponic	Showed a significant effect on the absorption of nutrients, except iron despite reducing the amount of chlorophyll in dry biomass leaves at high doses.	Dağhan (2018)

fodder maize seeds (Tondey *et al*., 2021). Hydroponic application using nano Si fertilizer, atonic, and nano complete fertilizer together increased the yield of Barley fodder. It is also found to be the best medium for increasing the dry matter, protein, and nutrient content (Al-Juthery *et al*., 2019).

NPs can enter a plant through stomata or other above-ground parts during foliar spraying. When soil application is followed, NPs can enter through the roots (Zhu *et al*., 2020; Avellan *et al*., 2021). Plant species, growth, soil characteristics, NP types, sizes, and interactions with the root zone and soil all affect the absorption of the NPs (Singh *et al*., 2020a; Al-Mamun *et al*., 2021). The diameter and concentration of the NPs play important roles (Pedruzzi *et al*., 2020). Two types of pathways, apoplastic and symplastic, are used in the absorption of NPs. The apoplast constitutes the xylem, cell walls, and intercellular space. This pathway facilitates the absorption of water and nutrients (Farvardin *et al*., 2020). Symplast pathway provides the movement by using plasmodesmata and neighboring cells. Several results suggested that the apoplast of the cell wall, which has a diameter of between 5 and 20 nm, represents the maximum size for absorption, translocation, and accumulation inside the plant system. The symplastic pathway is used for foliar uptake, while phloem is used to transfer the leaf to the shoot. However, there is not sufficient evidence in favor of the NPs' following phloem transport pathway in plants. The dimension of the NPs impacts the uptake. NPs are required to overcome a lot of physiological root barriers, like the cortex, epidermis, surface cuticle, and casparian strip (Lv *et al*., 2019). Conversely, NPs supplied through soil application can reach the plant through both apoplast and symplast routes (Pérez-de-Luque *et al*., 2017). NPs use the apoplastic pathway to move from the root to the upper portion (Lv *et al*., 2019). In contrast to the symplastic process, the apoplastic pathway appears to be faster. Some examples of using NPs as nutrient delivery in agriculture are given in Table 4.

THE APPLICATION OF NPs TO ALLEVIATE TARGET PESTS

Metal NPs offer significant benefits throughout all agricultural stages. Additionally, the development of nano-pesticides using NPs is very efficient compared to conventional fertilizers (Harish, *et al*., 2022). One major benefit of NPs is their minuscule size. NPs have a bigger surface area because of their small size and enable more pesticides to come into contact with insect pests (Rajna *et al*., 2019). In addition, they offer other benefits such as targeted distribution, less residues, regulated release of active substances, and preservation of beneficial insects (Su *et al*., 2022). They improve both the harvest index and the biological index. Because nano-pesticides minimize loss and adverse effects, the use of NPs is an environmentally friendly way (Shojaei *et al*., 2019).

The features of solubility of water-insoluble compounds can be utilized by nano-pesticide formulations to overcome the challenges associated with conventional pesticide application (Kamal *et al*., 2022). Plant species, insecticide kind, and application method all influence how metal NPs are made. According to Namasivayam, *et al*., 2023, nano gel is a popular formulation type in the synthesis of silver NP formulation. One such form involves creating re-dispersible dry emulsions by combining metal and metal oxide NPs, such as iron oxide, copper oxide, gold, and silver, with cellulose nanocrystals. An organic solvent, an emulsifier, a pesticide, and a few other ingredients comprise the emulsifiable nano-pesticide. Nonionic and polymeric surfactants are used to create oil-in-water emulsion, which serves as an alternative to emulsifiable nano-pesticide. In comparison to traditional pesticides, the particle sizes are 250 times smaller (Raj *et al*., 2021; Murthy *et al*., 2022). The most practical method for prolonging food shelf life in agriculture is encapsulation. Moreover, another kind of formulation is called nanodispersion, which consists of a blend of liquid media and nano-crystals. By offering a greater surface area, it helps the less water-soluble nanocrystals dissolve entirely in water. Less than 50 nm-sized nanocrystals dissolve more readily in water (kah *et al*., 2014).

Plant pathogenic bacteria and fungi can be inhibited with metal-based NPs. Pathogens and antibacterial systems interact directly (Li *et al*., 2023a). Metal NPs bind to sulfur and phosphorus in proteins and nucleic acids, decreasing membrane permeability, resulting in organelle and enzyme denaturation, and finally triggering cell death (Chaud *et al*., 2021). They improve the adhesion of pesticides to the insect's body, resulting in cell dehydration and a variety of histological and morphological abnormalities (Nie *et al*., 2023). Ag NPs break through the bacterial cell wall, raising intracellular osmotic pressure and ultimately leading to cell lysis. When applied to gram-negative bacteria, this NP works better than gram-positive bacteria. The explanation for this is that gram-negative bacteria have more lipopolysaccharide and either no or little peptidoglycan layer (Zhang *et al*., 2016). The waxy secretion of citrus mealybugs also contributes to the adsorption of silver NPs, enhancing the insecticide's anti-mealybug efficacy (Zaheer *et al*., 2022). Ag NPs saturated with carbons were found to cause harm to internal cellular tissues and the skin in another investigation (Sultana *et al*., 2018). Ag NPs are also important antifungal drugs that fight a variety of fungal-caused disorders. When combined with fluconazole, biologically produced AgNP has increased antifungal efficacy against *Candida albicans* (Mussin and Giusiano, 2022).

ZnO NPs are versatile and economically feasible for synthesis in large quantities, showcasing targeted antimicrobial properties and low phytotoxicity, making them suitable for combating various phytopathogens (Kalia *et al*., 2020). ZnO NPs can alter the permeability of the bacterial cell membrane by penetrating the cell membrane through the interaction of zinc oxide with the cell surface. As a result, it prevents cells from growing, resulting in oxidative stress and cell death. ZnO NPs are a great approach to protecting food from bacterial diseases in the food sector (Pavic *et al*., 2019; Dominic *et al*., 2022). Trypsin inhibitors such as Au NPs can impede the growth and reproduction of insects. There is little information available about how NPs affect insects and mites (Chaud *et al*., 2021). Plants respond better when NPs are used in addition to other NPs or other composite materials (Table 5). However, there is much potential for employing NPs as nano-pesticides, further research is still necessary to fill the knowledge gap.

EFFECTS ON IMPROVING PLANT GROWTH AND STRESS TOLERANCE

NPs are environmentally acceptable agricultural nutrition supplements that have benefits beyond fertilization and are easily absorbed by plants (Kaningini *et al*., 2022). According to a report, metal-based NPs show promise for managing diseases and pests that affect plants, as well as enhancing plant vigor and growth in a variety of stressful environments (Tortella *et al*., 2023). Mainly, two categories can be applied to metallic NPs. One category provides essential microelements to plants. Among them, copper (Cu), nickel (Ni), iron (Fe), and zinc (Zn) NPs can be specially mentioned (Santás-Miguel *et al*., 2023), not only for their impact on growth and development of plants (Pedruzzi *et al*., 2020; Nazarova, 2022; Zhou *et al*., 2023) but also for strengthening defense mechanism of plants against a range of biotic and abiotic stressors (Pullagurala *et al*., 2018; Iqbal *et al*., 2020; Salam *et al*., 2022). The second category does not supply essential microelements (Santás-Miguel *et al*., 2023), of which silver (Ag) and titanium (Ti) NPs are noteworthy for favoring the sprouting and growth of plants (Fatima *et al*., 2021; Mathew *et al*., 2021) and also for some healing effects on different microbial diseases. Some other NPs, such as gold (Au), selenium (Se), cerium (Ce), silicon (Si), and aluminum (Al) NPs, are also utilized, but to a lesser degree. These NPs have beneficial effects on specific plants and can raise the yield or safety of agricultural products (Santás-Miguel *et al*., 2023).

The concept of the development and growth of plant is wide and inclusive, including a plant's complete life cycle, from the process of a seed beginning to grow into a plant to the point where it reaches old age and starts to deteriorate (Gutiérrez-Ruelas *et al*., 2021). Plant growth and biological activity can both be enhanced by metal NPs (Hoang *et al*., 2019). Two varieties of metallic NPs are utilized in the development and growth studies of plants: pure metals and metal oxides. Each metal oxide nanoparticle (NP) possesses the ability to affect the development and growth of plants (Amin *et al*., 2021). Silver (Jhanzab et al., 2019), copper (Yasmeen *et al*., 2018), zinc, and iron oxide (Rizwan *et al*., 2019) NPs demonstrated improved growth (Hoang *et al*., 2019). Production of biomass, physiological and biochemical processes, development of shoots and roots, germination of seeds, enzymatic activities, nutrient elements, tolerance to stresses, all these indicators of growth

Table 5. Potentiality of NPs used as nano-pesticide in crops.

NPs	Pest	Impact	References
ZnO	Mealybug (*Puto barberi*)	Showed 55% effectiveness on the pest population.	Agredo-Gomez *et al*. (2024)
Cu-Ag	Thrips	Found effective in the thrips infestation. Also enhanced the chlorophyll content and antioxidant activity in the crop.	Mawale *et al*. (2024)
Cu-doped ZnO-NPs	*Spodoptera littoralis*	Showed a 95% reduction in the pest population. Cost-effective & Environment friendly.	Abd El-Latef *et al*. (2023)
ZnO NPs + thiamethoxam nanocomposite	*Spodoptera litura*	Increased the mortality of larvae and reduced the fertility rate.	Jameel *et al*. (2020)
(ZnO + TiO_2) NPs	*Bactericera cockerelli*	Significantly increased the mortality rate up to 100%.	Gutiérrez-Ramírez *et al*. (2021)
TiO_2	*Ralstonia solanacearum*	Enhanced disease resistance and increased antibacterial activity.	Pan *et al*. (2023)
CuO NPs	*Spodoptera frugiperda*	Increased the antifeedant activity in larva and proved as environment-friendly method.	Rahman *et al*. (2022)
Cu NPs	*Tribolium castaneum*	Proved the toxicity against the stored grain pest. It can be used as a cost-effective approach for controlling stored pests.	El-Saadony *et al*. (2020)
Fe NPs	*Tuta absoluta*	Showed a 50% mortality rate in the pest. Proven as beneficial for agriculture.	Ramkumar *et al*. (2021)
TD NPs	*Helicoverpa armigera*	Act as an inhibitor to the development of the pest.	Chinnaperumal *et al*. (2018)

and also yield, yield quality, freshness, and shelf life are positively affected by NPs (Amin *et al*., 2021). Additionally, NPs are capable of penetrating the chloroplasts of plants and go to the reaction center of the photosystem-II (PS-II). Once inside, NPs enhance electron transport and light absorption in chloroplasts, enhancing the efficiency of photosynthesis and stimulating plant development (Maity *et al*., 2018).

Some specific advancements of plant growth in recent times can be summarized as: increased biomass in corn by silver (Ag) NPs; improved antioxidant activities, proline content, leaf area, and photosynthetic rate in tomato by ZnO NPs; increased root length, lateral roots, and plant height in larch by SiO2 NPs; enhanced seedling growth, shoot-root length, and photosynthesis efficiency in maize, watermelon and squash by Ag NPs; enhanced vegetative growth in barley and increased plant height, stem diameter, pods, seeds, sugar content in Indian mustard by Au NPs; leaf area, dry weight plant height increased in wheat by Fe and Zn NPs; tomato's yield production and chlorophyll content along with seed germination rate of chickpea are enhanced by TiO_2 NPs and many more (Verma *et al*., 2021).

Under stressful conditions, NPs exert a critical influence on the molecular, physiological, and biochemical aspects of plants (Rasheed *et al*., 2022). Their main function is to inhibit the plant's reactive oxygen species (ROS) response while promoting plant development and growth by controlling the antioxidant systems and internal plant hormones. They additionally influence how stress-related genes are regulated during transcription (Tripathi *et al*., 2022). Recently, NPs have enhanced a plant's ability to withstand both biotic and abiotic stressors. By enhancing the functions of antioxidants, they save plants from oxidative harm (Ahmed *et al*., 2021c).

NPs might mitigate the detrimental effects of drought by reducing the production of malondialdehyde (MDA) and hydrogen peroxide (H_2O_2), while maintaining the effectiveness of the photosynthetic system (Adrees *et al*., 2020; Ahmed *et al*., 2021d). The toxic impacts of salt stress on diverse plant species were successfully minimized through the utilization of the following NPs: iron (Fe), potassium (K), copper (Cu), titanium (Ti), carbon (C), zinc (Zn), cerium (Ce), silver (Ag), manganese (Mn), and silicon dioxide (SiO_2) (Zulfiqar and Ashraf, 2021). The implementation of NPs in different concentrations to alleviate the consequences of thermal stress led to improved plant development and hydration (Ali *et al*., 2021). In plants impacted by heavy metals, NPs (NPs) provide membrane stability and increase the rate of photosynthesis and chloroplast pigmentation (Ahmed *et al*., 2021a).

NPs can influence pathogens directly or fortify defenses by decreasing fungal, viral, and bacterial infections, increasing plant nutrition, and improving crop production and nutrition quality (Kah *et al*., 2019). Metal NPs employ various antimicrobial processes to take direct action against external organisms. They are capable of causing electron transport to be impeded, DNA destruction, and membrane rupture through the internalization and release of ions. Additionally, they have the ability to produce ROS, which can damage DNA and disrupt enzymes, as well as denaturize proteins (Tortella *et al*., 2023).

USED AS NANO-SENSORS AND NANO-PRIMING AGENT

Precision farming offers farmers a viable substitute by minimizing the use of agrochemicals and offering crop-specific solutions tailored to specific sites. This strategy reduces the need for pesticides, fertilizers, and herbicides while increasing crop yields (Yadav *et al*., 2023). With the improvement of diagnostic methodologies and equipment, nano-biosensors have been crucial in transforming farming, and these sensors are precise, effective, and affordable when it comes to addressing an extensive array of food, environmental, and agricultural challenges (Johnson *et al*., 2021). Nano-biosensors possess the capability to identify and track a multitude of environmental and plant health-related parameters. Furthermore, these diminutive apparatuses are capable of premature detection of pathogens, pests, and diseases, which facilitates prompt intervention and mitigates crop losses (Miguel-Rojas and Pérez-de-Luque, 2023). Nano-sensors ought to possess the following characteristics: portability, affordability, non-toxicity, high target specificity, and precise, accurate, and reproducible performance. They are also used in agriculture to analyze various factors such as fertilizers, herbicides, insecticides, diseases, soil texture, and their controlled application to improve crop output (Rai *et al*., 2012). *Ralstonia solanacearum,* which causes bacterial wilt in tomatoes, can be targeted by nano-sensor gold NPs functionalized with ssDNA through colorimetry mechanism (Khaledian *et al*., 2017). Uses of gold NPs also include the detection of sweet corn infection with the gram-negative bacteria *Pantoea Stewartii sbusp. Stewartia* (Zhao *et al*., 2014). Besides, silver and zinc oxide NPs are used to target *Trichoderma harzianum* (Siddiquee *et al*., 2014) and *Phytophthora ramorum* (Yüksel *et al*., 2015), respectively. Monitoring and regulating the use of pesticides, fertilizers, and other chemical substances provides valuable data for precision agriculture (Duhan *et al*., 2017). For example, ZnO QDs were applied to kasugamycin to improve its photo-stabilization property along with achieving synergistic antimicrobial activity (Liang *et al*., 2019), and another example is targeting fenitrothion through electrochemical mechanism, which is done by nano titanium dioxide (Kumaravel and Chandrasekaran, 2011). The nano formulation of herbicides functions as an intelligent delivery mechanism for the active component, therefore decreasing the overall concentration of the chemical compound and nanoencapsulation enhances the ability of herbicides to penetrate through the cuticle and enables a gradual and regulated release of the chemical active component (Amodeo *et al*., 2022).

The process of seed germination includes bidirectional interactions between the embryo and the endosperm, with the endosperm functioning as an environmental sensor that governs the development of the embryo and the embryo regulating the destruction of the endosperm (Yan *et al*., 2014). Seed germination in normal conditions sometimes does not touch the expected level, and here nano-priming or seed priming is a great solution. Nano-priming is a unique way of seed priming that helps to boost growth, yield, and germination of seeds by giving plants resistance to a range of stresses (Nile *et al*., 2022). Under both normal and stressful circumstances, nano-priming helps seeds regulate their reactive oxygen species (ROS), and it also increases the pace at which seeds germinate and produces more robust, better seedlings (Kandhol *et al*., 2022). In arsenic stress, seed priming with zinc oxide NPs (concentrations @10, 20, 50, 100, and 200 mgL^{-1}) enhances the seed germination rate of rice (Wu *et al*., 2020b). Besides, they also enhance the seedling growth of fragrant rice varieties in cadmium stress (Li *et al*., 2021). Silver NPs are very helpful for mitigating stress conditions while seeds are primed with them. Seed priming of fenugreek and lentil seeds increases seed germination during salt stress (Hojjat and Kamyab, 2017) and drought stress (Hojjat and Ganjali, 2016), respectively. At the dose of 0, 500, 1000, and 2000 mgL^{-1}, Titanium dioxide NPs enhance primed wheat seed germination in drought stress (Faraji *et al*., 2018) and also in cadmium stress (Faraji and Sepehri, 2019).

Harmful effects and environmental fate of using metal NPs

Agricultural practices can employ metallic NPs for various purposes, primarily aiming to increase crop yield through the application of seed priming, plant protection, biosensing, nano-fertilizers, growth stimulators, and nano-pesticides. Additionally, metallic NPs can be employed to address the contamination of both water and soil resulting from farming activities (Spanos *et al.,* 2021). In agriculture, NPs are used 42% for fertilizer, 10% for plant breeding, 26% for animal husbandry, 4% for soil enhancement, and 18% for plant protection (StatNano, 2022). Although metal NPs have numerous advantages, there are still many unknowns when it comes to how these materials may have a long-term impact on the environment (da Silva Júnior *et al*., 2022). Physical and chemical properties, manner of use, stability of NPs, strength, pore size, precise dimensions, area of contact, availability for biological uptake, maturity, the improper combination, length of exposure, and type of plant are some of the variables that might cause NPs to be harmful in agriculture (Li *et al*., 2022; Liu *et al*., 2022; Sun *et al*., 2022). Comprehending these variables is crucial in evaluating the possible hazards associated with the utilization of NPs in agriculture (Balusamy *et al*., 2023).

Although the precise processes of nanoparticle toxicity remain unclear, researchers have documented that the harmful effects of NPs are influenced by the following factors: (i) the NPs' tendency to bioaccumulate due to the fact that the majority of engineered NPs lack biodegradability (Yoo-Iam *et al*., 2014); (ii) the NPs' reduced diameter, which allows for their translocation and penetration into biological structures such as cellular membranes and tissues (Ma *et al*., 2011; Yin *et al*., 2012); and (iii) the ability of NPs to traverse trophic levels within ecosystems facilitates biomagnification at elevated trophic levels (Judy *et al*., 2011). Many unanswered concerns remain regarding their behavior, destiny, and effects on plants (Scherer *et al*., 2019).

When plants are enriched with NPs, their physiological processes are typically altered by a decrease in transpiration and photosynthesis, which ultimately impacts plant development (Rajput *et al*., 2018). The suppression of seed germination, the reduction in light synthesis, and the disturbance of plant roots are among the many negative consequences of NPs that have been documented (Singla *et al*., 2019). Research findings indicate that NPs may shorten roots and stems by slowing down the germination process. Certain NPs not only detrimentally affect plant growth but also damage cells and subcellular organelles, impairing mitochondrial function and cell membrane integrity (Gao *et al*., 2023). Additionally, they may affect plant growth by interfering with photochemical synthesis, altering the function of antioxidant enzymes, causing oxidative damage, and causing an imbalance in the nutritional makeup of crops intended for human consumption (Siddiqi and Husen, 2017; Lian *et al*., 2020) (Fig. 5).

These nanomaterials might potentially affect vital biological functions through their interactions with living things (Burketová *et al*., 2022). Some NPs, when transmitted to and deposited in plants, can cause phytotoxicity (Gao *et al*., 2023). The mechanisms underlying plant toxicity caused by NPs involve three distinct processes that occur upon the interaction between NPs and plants: (i) they make it easier to produce ROS, which is harmful because of oxidative stress (Marslin *et al*., 2017); (ii) they trigger a transcriptional response (Xun *et al*., 2017); (iii) their genotoxic effects, resulting from their interaction with DNA or organelles (such as mitochondria) (Ghosh *et al*., 2019). Once absorbed by plants, NPs have the ability to move through the vascular system to other tissues. Once in these tissues, they can cause oxidative stress, enhance chromosome aberration index and micronucleus, as well as genotoxic and cytotoxic effects on plants that impact root elongation and plant seed germination. (Khan *et al*., 2019c; Scherer *et al*., 2019). Several investigations reported about NPs' genotoxicity and harmful effects on a plant's DNA and other genetic components. This may result in chromosomal aberrations, mutations, or other genetic alterations in plant cells, which could have a damaging impact on the plant's general health, development, and growth. These genetic changes could affect the plant's capacity to replicate, adapt to environmental stressors, also defend against infections (Mutlu *et al*., 2018; Sharma, 2023).

Some specific examples of negative effects by NPs can be summed up as: Ag NPs had a detrimental effect on the growth of cucumber plants, specifically on the length of the roots and stems, as well as the fresh and dry weight of the plants, resulted in deduction of carotenoids in the seedlings as well as a drop in overall biomass and the levels of chlorophyll content; also inhibited photosynthesis and reduced zinc and iron nutrients (Tripathi *et al*., 2017); toxicity of ZnO NPs on *A. thaliana* showed chlorosis, lateral roots inhibition, and leaf size reduction ultimately resulting in decreasing the level of micronutrients (Nair and Chung, 2017); root elongation of *A. thaliana* significantly reduced when exposed to carbon particles and that also kept reducing with an incremental rise in the dose (Chen *et al*., 2018; Gao *et al*., 2023); obstruct root pore structures and reduce transpiration and cell membrane fluidity of wheat

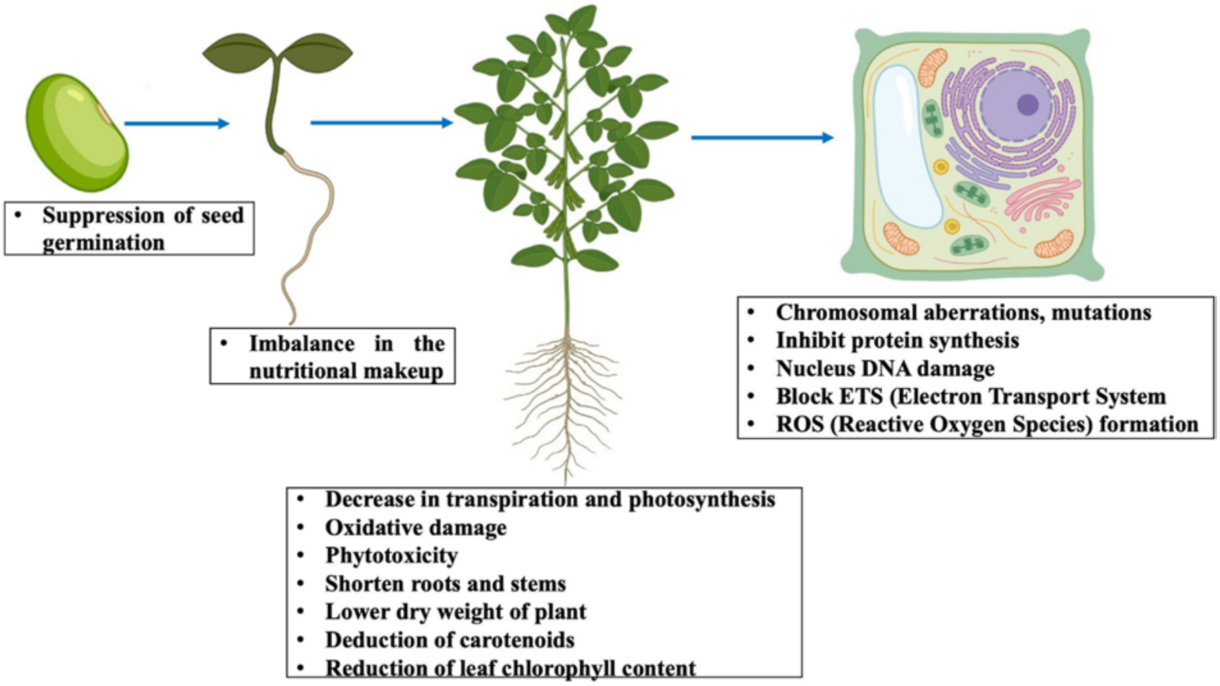

Fig. 5. Negative impacts of metal nanoparticles in plants.

(He *et al*., 2021; Feregrino-Perez *et al*., 2023); suppressed microbial symbiosis in the vicinity of plant roots of rice by TiO2 NPs (Khan *et al*., 2021); caused DNA damage, with cytotoxic and genotoxic effects on the root meristem of onion by Si NP (Liman *et al*., 2020); reducing leaf chlorophyll content and biomass of maize and many more (Shukla *et al*., 2024) (Fig. 5).

Metal NPs used in agriculture could upset environmental equilibrium, particularly for soil microbes (Saha *et al*., 2022). They hold the possibility of adversely affecting a variety of non-target microbiological functions, including the synthesis of organic matter, chemical mineralization, and nutrition cycling (da Silva Júnior *et al*., 2022). The presence of nanoparticles in the soil results in two potential effects: direct toxic effects on microbes as well as modifications to environmental physiochemistry (Dimkpa, 2014). The modifications made to soil environment through metal NPs have the ability to negatively affect critical ecosystem services which include organic matter decomposition along with nutrient mineralization. The transformation of metal NPs in the soil has the potential to produce soluble metal ions that would harm plant organisms and soil microbes (Mishra *et al*., 2017). Besides, conventional NPs are produced in ways that are both environmentally damaging and expensive (Jiang *et al*., 2022; Saritha *et al*., 2022). On the other hand, numerous investigations also demonstrated that plant-mediated NPs have little to no ecotoxicity toward plants in general (Plachtová *et al*., 2018). This dual consideration of enhanced agricultural productivity versus potential ecological risk necessitates a balanced approach in the application of nanotechnology in agriculture (Fig. 6).

For the technology to be transferred from the lab to the field, NPs toxicity is a crucial standard. In an effort to reduce the toxicity of NPs, scientists have coated them with various moieties; nevertheless, as of right now, no thorough study that addresses the long and short-term impacts of NPs on plants and plant-associated food chains is accessible (Balusamy *et al*., 2023). These emphasize how crucial it is to comprehend and properly evaluate how NPs and plants interact in agricultural applications (Shukla *et al*., 2024). Despite all these reservations, NPs hold immense promise as an emerging technology in agriculture (Balusamy *et al*., 2023).

Impacts of concentration, size, and forms of metal NPs on their performance

NPs can improve crop production and resistance to various stresses, but their use requires understanding their pros and cons for efficient use in agriculture (El-Moneim *et al*., 2021). The effects of NPs on germination and seedling growth might vary depending on their size and concentration (Szőllősi *et al*., 2020). Negative effects of metal NPs are contingent upon plant species, concentration, shape, and size. (Chaud *et al*., 2021; Hassanisaadi *et al*., 2022b). For example, higher concentrations of AgNPs exposed to seeds showed phytotoxicity, but treated seeds containing 100 and 200 μL of AgNPs biosynthesized by *Fusarium semitectum* may increase seed germination and shoot and root length (Singh *et al*., 2016). Besides, at 30 μg/mL concentrations, AgNPs were shown to be the most efficient enhancer in growth and germination of *Silybum marianum*, although inhibitory effects were seen at higher NPs concentrations (Salman Khan *et al*., 2016). From the research of Jadczak *et al*., (2019), lavender seedlings showed enhanced growth, plant weight, and longer roots when exposed to AuNPs concentrations (2, 5, and 10 mg dm^{-3}), while high doses reduced shoot length and growth parameters. The morphological characteristics of plantlets of *Stevia rebaudiana* changed as a result of the negative impacts of FeNPs at high concentrations, whereas at low concentrations, considerable benefits of FeNPs were seen (Khan *et al*., 2020). Zinc was used as a trace element and is only partially needed by plants (0.05 mgL^{-1}). Too much zinc might have detrimental consequences on plants (Verma *et al*., 2018). High concentrations of CuNPs (400 and 800 mgL^{-1}) caused phytotoxicity effects in *Coriandrum sativum* (Gao *et al*., 2018). According to Hassanisaadi *et al*. (2022a), impacts of using high and low concentration of NPs on plants are shown in Table 6.

The size of NPs has an impact on their performance. Size-dependent phytotoxicity was shown by small-sized ZnO NPs (5, 20, and 50 nm), which inhibited rice length and biomass (Li *et al*., 2023b). Essential elements (Cu, Zn, and Fe) sprayed on

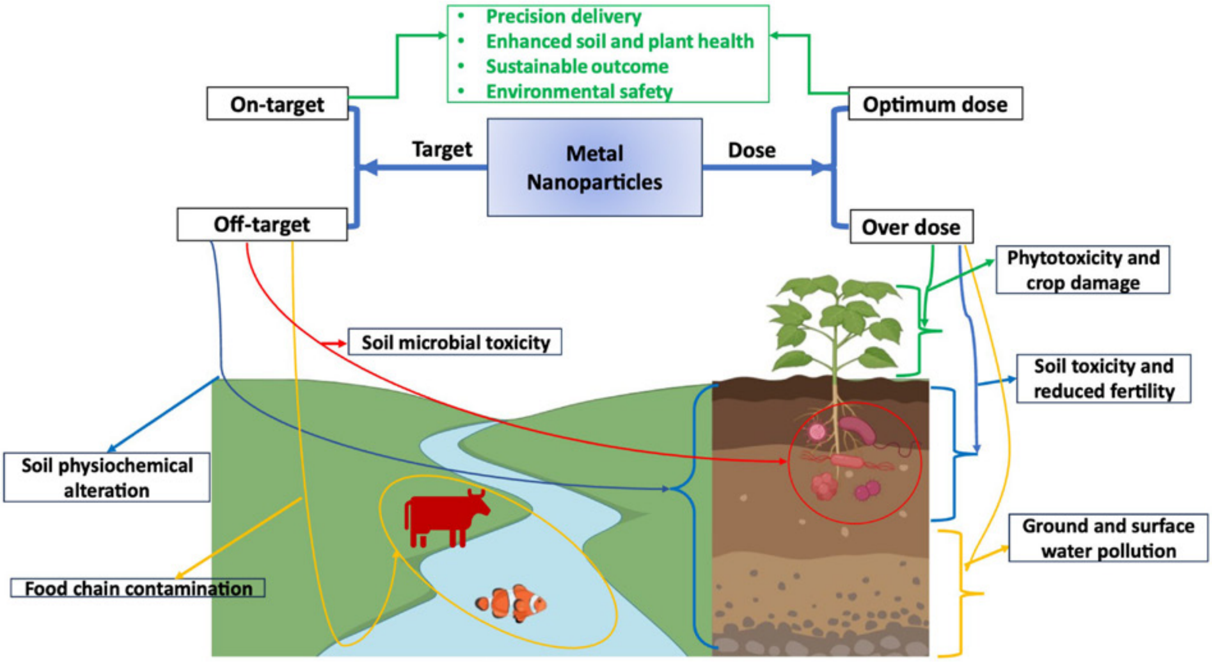

Fig. 6. Environmental fate of using metal nanoparticles for crop production.

Table 6. Differences between the impacts of using NPs at high and low concentration on plants.

High concentration	Low concentration
Show phytotoxicity	Show simulative effect
Decrease seed germination	Increase seed germination
Decrease root elongation	Increase root elongation
Decrease shoot elongation	Increase shoot elongation
Increase oxidative reaction	Decrease oxidative reaction

the foliage as tiny metallic NPs may be more effective in being absorbed by crops than dissolved metals (Jia *et al*., 2023). 50 nm-sized bimetallic Ag/Au NPs were least hazardous to lupin and most poisonous to flax (Szymanski and Dobrucka, 2021). The development of seedling roots was inhibited and the carbohydrate profiles of wheat seedlings were rearranged by smaller Ag NPs (10 and 20 nm in size) (Lahuta *et al*., 2022). However, nano forms of NPs, which are used as different agricultural inputs, are better than the bulk forms of other agrochemicals (Table 7).

Future perspectives

The significant hazards to the environment and human health have caused researchers to refocus their efforts on biologically derived metal NPs (NPs) and their environmentally benign, economically viable, and sustainable synthesis. The productivity of agroecosystems may be raised by the use of NPs in a variety of ways, including nano-pesticides, nano-herbicides, nano-fertilizers, nano plant growth promoters, and nano-nutrient transporters (Hossain *et al*., 2023). Metal NPs can improve the whole process from seed germination to yield, along with food quality. Including appropriate size and dose, metal NPs may be engineered to target certain plant regions, delivering nutrients or pesticides directly to where they are needed maximizing nutrient uptake, and reducing runoff into waterways. So, metal NPs can be used as fertilizer, which will reduce farmer's costs and also will be eco-friendly by confirming pollution-free environment. They have the ability to increase seed germination even in stressed conditions, which indicates that they can enhance seed vigor and viability and can be used in those crops that have low germination percentages and higher seed rates. After confirmation of seed germination for achieving expected yield, the physiological process of plants should be improved, which can be made possible by using these metal NPs without toxic effects. For better photosynthesis rate, better respiration, enhanced physiological reaction, boosted chlorophyll content and stomatal opening, facilitated redox reactions, greater stability, increased defense enzyme activity, elevated antioxidant activity, etc., metal NPs can be more effective for plants and lead to sustainable agriculture. At the matured level and pre-harvest conditions, these metal NPs can be more effective due to enhancing the grain's protein and lipid content, useful acid content, and weight, along with forming secondary metabolites, which will smooth the biofortification process. This indicates that, in the future, these NPs will be used in every agricultural sector to produce food and feed the hidden hunger all over the world. This will contribute to achieving Sustainable Development Goals (SDG). Metal NPs have natural antimicrobial capabilities, which include antibacterial, antifungal, and antiviral activities, and these qualities may be used to assist in the fight against pests and illnesses that affect crops. Future developments might lead to the creation of formulations based on nanomaterials that can specifically target dangerous diseases while protecting helpful bacteria in the soil. This focused approach to pest control lessens the need for chemical pesticides, lowering environmental hazards and enhancing ecosystem health. Metal NPs could be engineered to confer tolerance to abiotic stresses related to drought, oxidative damage, heat, cold, etc. This holistic approach would provide plants with comprehensive resilience against various environmental challenges, thereby contributing to sustainable agriculture in diverse ecosystems. So, the use of metal NPs in precision and sustainable agriculture has enormous potential for increasing crop resilience and maintaining food security in the face of escalating environmental concerns. Using nanotechnology, we can create bespoke solutions that maximize resource usage, reduce environmental impact, and promote agricultural sustainability.

Conclusion

Despite the unexpected consequences, negative environmental impact, and toxicity sometimes, metal NPs have a positive and

Table 7. Comparative table of nano form and bulk form of agricultural inputs (fertilizer).

Comparison items	Nano forms	Bulk forms
Bioavailability	High bioavailability	Low bioavailability
Efficiency of nutrient uptake	This boosts the efficiency of nutrient uptake (50–70%) and is always available for roots	This lowers the efficiency of nutrient uptake (20–50%) and not available for roots
Effective nutrient release duration	Long-term (up to 50 days) nutrient supply in the soil	Short term (up to 50 days), depends on nutrients
Controlled release	Release pattern and rate are finely regulated due to coating or its encapsulation	Soil imbalance and severe toxicity are caused by excessive nutrient release.
Mineral nutrients' solubility	Improved solubility	Lower solubility
Mineral micronutrient dispersion	Enhance insoluble nutrient dispersion	Reduced solubility as a result of the large particles
Rate of loss	Minimal loss of nutrients from fertilizer	Elevated loss rate due to leaching, drifting, and run-off

Source: Seleiman *et al*. (2020); Rizwan *et al*. (2021); Kalwani *et al*. (2022); Shalaby *et al*. (2022).

significant impact, including growth promotion, stress mitigation, yield enhancement, etc., on the plant's life cycle. Thus, metal NPs have become a promising topic that leads to precision and sustainable agriculture. Besides, the green synthesis method of metal NPs is an eco-friendly method requiring less time, money, and energy, is more suitable for sustainable agriculture, and can be used in the farmer stage. To feed the increasing population without doing harm to the environment, we should use these metal NPs in an appropriate size and in an ethical manner. As there is much ongoing research on metal NPs in agricultural sectors all over the world, the researchers should focus on the mitigation of risk factors for metal NPs. They should try to ensure a better outcome in the future.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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