Potentiality of Metal Nanoparticles in Precision and Sustainable Agriculture

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Abstract

The world's increasing population has a higher demand for food and a suitable environment. However, using conventional farming methods and industrial agrochemicals leads to environmental risk, which is a significant threat for the next generation. So, nanotechnology can be a blessing for saving our environment and producing risk-free foods at minimal cost in an eco-friendly way. Nanoparticles (NPs) used as nanopesticides, nanofertilizers, nanosensors, nanopriming agents, and other applications in agriculture can help mitigate issues such as high production costs, excessive pesticide and fertilizer requirements, soil depletion, and various biotic and abiotic challenges. A variety of important information from different research findings on metal nanoparticles, their characteristics, the synthesis process, and their roles in precision and sustainable agriculture are included in this article. This literature review discusses the benefits of metal nanoparticles on plant growth and development, the ease of green nanoparticle production over chemical and physical approaches, and the effects of metal nanoparticles on agriculture. Future perspectives for metal nanoparticles are also covered in this article based on these impacts. Metal nanoparticles, used as biosensors and seed-priming materials, can contribute to seed germination even in adverse conditions. So, overall, this review article discusses the potentiality of using metal nanoparticles in lieu of inorganic agrochemicals and their possible contribution to precision and sustainable agriculture.

Keywords: *Metal nanoparticles; Sustainable agriculture; Environmental risk; Nanoparticles;*

1.Introduction

Nanotechnology refers to the investigation of substances ranging in size from one to one hundred nanometers (Joudeh & Linke, 2022). Nanoparticles (NPs) are exceedingly minute metal particles that have the capability of integrating diverse active principles to form an integrated system. This integration allows the NPs to operate within an experimental organism, ultimately improving the organism's overall health (Baker et al.,2015). The numerous applications of NPs in agriculture can be attributed to their special characteristics, which include their tiny size, increased surface area to volume ratio, physical strength, reactivity, and optical, electrical, and magnetic properties (Hazarika et al., 2022). In the agriculture industry, these distinctive features of NPs have sparked extreme alarm.

The number of people in the world is constantly growing, and these restlessly growing people's desire for food is equally increasing. 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., 2020a). Industrialization also became hazardous for the environment, lowering the natural resources for food production. This also increases the need for increasing food production with maintaining the biodiversity. Farmers have long used traditional methods, which have limited agricultural output due to increased fertilizer consumption, environmental contamination, microorganism-causing diseases, and abiotic stressors (Jhing et al., 2022).

The next green revolution will be built on precision farming, which monitors environmental factors and implements targeted measures to maximize output (economic yield) while limiting input (pesticides, fertilizers, herbicides, etc.) (Panpatte et al., 2016). Nanotechnology is essential for sustainable agriculture development. By implementing innovative approaches that increase plant productivity through the deft addition of nanonutrients for nanoherbicides, nanofertilizers, and nanopesticides by the plants, has the immense potential to completely transform the agricultural sector (Aslam et al., 2022). Metal NPs can be synthesized biologically, chemically, or physically. There are benefits and drawbacks to each of the three ways, but the biological synthesis method—also known as "green synthesis"—is the most advantageous. Farmers frequently employ pesticides and fertilizers to boost output, which is primarily lost by leaching, runoff, and other factors (Mittal et al., 2020b). This raises production costs and reduces biodiversity. NPs are 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). The most popular metal nanoparticles for antibacterial applications are zinc (Zn), silver (Ag), and copper (Cu). Copper NPs are widely used in agriculture for a range of applications because they are somewhat more cost-effective and readily available (Hazarika et al., 2022). Increased agricultural productivity can be achieved by using NPs as nutrient elements for improved germination, controlling vectors and pests, using nanosensors for pest detection, efficiently dosing water and fertilizer, using nanoporous zeolites for slow release, delivering herbicides via nanocapsules, and creating nanofertilizers (Ditta et al., 2015).

This research emphasizes the possible use of metal nanoparticles in sustainable agriculture. It addresses metal nanoparticles, their synthesis method, and their advantageous role in enhancing precision agricultural production. The contributions provided by NPs will undoubtedly change the challenges that farmers encounter.

2. Commonly used metal nanoparticles

The field of science and engineering that studies materials with dimensions of one-hundredth of a nanometer or less are known as nanotechnology (Mody et al.,2010), and there are two categories for this large class of nanomaterials: metallic and non-metallic nanoparticles (Yih and Al-Fandi,2006). Metal-based nanoparticles 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 & Chauhan, 2019; Sharma *et al.,* 2022; Vijayanandan & 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). Table 1 shows the many uses of NPs in agriculture. NPs are useful for controlling plant nutrition, phytopathogen protection, plant growth regulators, and nanofertilizers (Figure 1).

2.1. Iron oxide nanoparticles

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 iron nanoparticles are extracted from different plant species, and their size ranges from 0-150nm (Abegunde *et al.*,2020). For many cellular enzymes in organelles, iron is a critical factor in determining their biological activities, and these enzymes are essential for photosynthesis, respiration, and the quality of goods made from plants (Vigani *et al.*, 2013; Briat *et al.*, 2015).

2.2. Titanium dioxide nanoparticles

There are two types of titanium dioxide based on structure: rutile and anatase (Chen and Mao,2007). TiO_2 nanoparticles boost the plant's immunity and photosynthetic rate, which raises crop output by 30% (Waghmode *et al.*,2019) and the development of plants is said to benefit from it. Plants can also benefit from its application in nano form to increase production and growth (Faraz *et al.*,2020). Before sowing, TiO_2 seed treatment increased spinach chlorophyll content, rate of photosynthesis, and dry weight of the plant (Zheng *et al.*, 2005).

2.3. Silver nanoparticles

The most prevalent metallic nanoparticles with antibacterial properties are silver nanoparticles, and they are utilized to treat plant diseases (Mishra & Singh, 2015) and improve the efficacy of fungicides, plant growth, and fruit ripening in agricultural settings (Mahendran *et al*.,2019). Spherical shaped (1-100nm) silver nanoparticles 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).

2.4. Zinc oxide nanoparticles

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). It is a cofactor for the majority of enzymes, including superoxide dismutase, carboxypeptidase, and carbonic anhydrase (Rizwan *et al*., 2019; Saifullah *et al*., 2016). Zinc nanoparticles can take many forms, including rods, plates, spheres, boxes, hexagons, tripods, tetrapods, wires, tubes, rings, cages, and even flowers (Siddiqi *et al.*,2018).

2.5. Magnesium oxide nanoparticles

Because of their exceptional physicochemical properties, which include outstanding corrosion resistance, low electrical and high thermal conductivity, exceptional refractive index, physical strength, etc., magnesium nanoparticles (MgO) are environmentally friendly, commercially viable, and industrially significant nanoparticles, and their different shapes (spherical, cubic, nano-flower, rod-like, cluster, hexagonal, etc.) are seen during green synthesis (Abinaya *et al.*,2021). They act as an anti-microbial agent, increase insect tolerance of plants, enhance agricultural production, activate defense signaling pathways in plants, and are suitable for precision farming (Fernandes *et al.*,2020).

2.6. Cobalt oxide nanoparticles

The magnetic characteristics of cobalt oxide nanoparticles 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). When administered in small amounts, they contribute to plant development in every phase, facilitating crucial chemical and biological interactions (Singhal *et al.*,2023). Additionally, they have been seen to benefit plants during drought stress (Brengi *et al.*,2022).

2.7. Copper oxide nanoparticles

Variable microelectrode potential, renewable surface area, and a high surface-to-volume ratio make copper nanoparticles popular catalysts (Din and Rehan,2017). Copper nanoparticles (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, and these nanoparticles are crucial micronutrients for crop development. Cuprous oxide and cupric oxide

(Bakshi and Kumar, 2021). It is necessary for plant development, and it is also used as a bactericide and fungicide. Studies have shown that it is more effective in preventing a variety of common bacterial and fungal illnesses (Rai *et al.*,2018).

2.8. Cerium oxide nanoparticles

A member of the lanthanide group, Cerium is the most prevalent rare metal with catalytic capabilities (Singh *et al.*,2020a). 5-30 nm sized cerium nanoparticles can be extracted from plant species like *Acalypha indica, Olea europaea, Hibiscus Sabdariffa* etc. Nanoceria have antibacterial, anticancer and antioxidant activity (Rajeshkumar and Naik,2018). In agricultural sector it is used for crop improvement and stress tolerance (Singh *et al*.,2020b).

2.9. Gold nanoparticles

Gold nanoparticles 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 nanoparticles 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). Uses of gold nanoparticles include bio-catalysis and pathogen detection, and they are used as biosensors also (Santhosh *et al.*,2022). The beneficial effects of these metal nanoparticles on plants are listed in Table 1.

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

Name of metal nanoparticles	**Applications/functions**	**Sources**
Iron oxide nanoparticles	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	Singh *et al.*,2021

	are facilitated by the presence of iron.	
	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
Titanium dioxide nanoparticles	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 $\mathrm{mgL^{-1}}$), 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 $\mathrm{gL^{-1}}$) 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 m $\mathrm{gL^{-1}}$ and particle size of around 20 nm.	Shende *et al.*,2021

Zinc oxide nanoparticles	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 a 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
Silver nanoparticles	1. In drought-stressed conditions, administered at a concentration of 10 μgmL^{-1}were observed to increase lentil seed germination.	Hojjat *et al.*,2016
	2. Administration of AgNPs improved salinity tolerance in *S. hortensis* seedlings and activated plant defense mechanisms against salt toxicity.	Nejatzadeh *et al.*,2021
	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.*,2023
	4. When treated with 6 μgmL^{-1}of AgNPs, there were significant increases in fresh and dry weights and an	Khan *et al.*,2023

	incitement to the production of secondary metabolites of wheat plants.	
	5. At 75 ppm exhibited 75% mortality and are effective against pests and beetles.	AS *et al.*,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
Magnesium oxide nanoparticles	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.*,2021
	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.*,2022
	5. 30% to 50% improvements in yield of maize were observed, and the grains' nutritious content was positively impacted	Segatto *et al.*,2023
	6. A notable antibacterial impact was noted against the rice pathogen A. oryzae.	Ahmed *et al.*,2021
Cobalt oxide nanoparticles	1. Cobalt nanoparticle-infused barley seeds boost production without having any harmful effects.	Seregina *et al.*,2021

	2. Cobalt nanoparticles measuring 11.4 nm are absorbed by the 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 nanoparticles 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
Copper nanoparticles	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
	2. The antifungal efficacy was investigated against *Furnarium oxysporum and Alternaria solani* which fungi are harmful to tomato.	Vinod *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 fungus 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

Cerium oxide nanoparticles	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
Gold nanoparticles	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

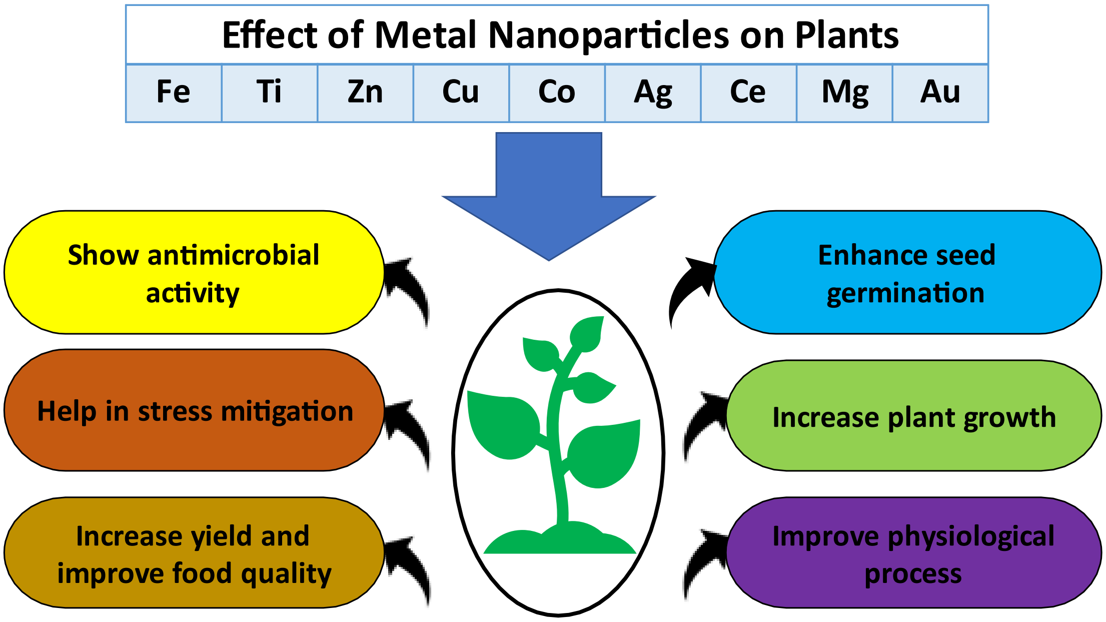

Figure 1. Beneficiary effects of metal nanoparticles on plant

3. Synthesis methods of metal nanoparticles

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 nanoparticles 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 (Figure 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.

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

Merits/Demerits	**Approaches**		
	Top Down	**Bottom Up**	
	Physical Synthesis Method	**Chemical Synthesis Method**	**Biological/Green Synthesis Method**
	• Mechanical grinding • Arc discharge • Thermal/ laser ablation • Laser pyrolysis • Ultrasonication • Sputtering • Vapor phase synthesis • Radiolysis • Ion implantation • Electro exploitation • Inert gas condensation • Pulse laser deposition • Evaporation condensation • Flash spray pyrolysis • Etching (Chemical)	• 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	• Microbes (Fungi, virus, bacteria, yeast) • Plants • Algae

		precipitation • Solvothermal • Spinning • Aerosol-based process	
Merits	• 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 nanoparticles are mutable • Formation in	• 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 nanoparticles	• Nanoparticle size is regulated and less harmful. • Utilization of compounds with lower toxicity. • Consistent nanoparticles. • Energy savings. • Great output. • Super cheap. Consistent results. • Created a rather homogeneous particle • Firmly adhere to the substrate (Major advantage)

	liquid media without the use of surfactant • Adaptable method for creating ionic nanoparticles		
Demerits	• 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 nanoparticles are among the factors	• 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 nanoparticles. • Challenging large-scale manufacturing. • costly approach • Produce a small amount of material • Multicomponent deposition presents challenges. • restricted	• Gradual synthesis process. • Risk to safety cost of • Production is increased by heating conditions.

	contributing to the mass production of trash. - Ablation rate reduction - Unwanted contamination - Very sensitive microstructure that can be ground	repeatability	

[Source: Ndaba *et al.*,2022; Kaningini *et al.*,2022; Jamkhande *et al.*,2019; Iravani,2011]

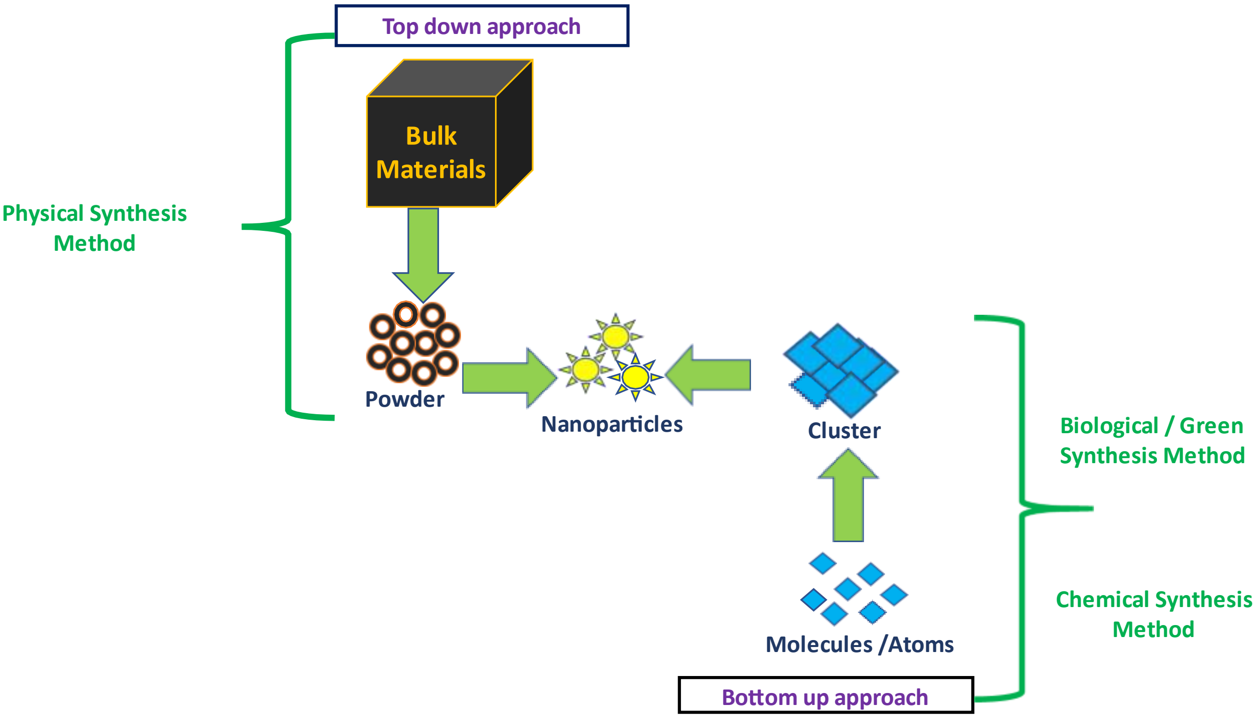

Figure 2. Different synthesis approaches for metal nanoparticles.

3.1. Physical method of synthesis

There are specific impacts of using nanoparticles 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:

3.1.1. 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).

3.1.2. 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.*, 2017a). 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.*, 2017b).

3.1.3. Pulse 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 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).

3.1.4. 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).

3.1.5. 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).

3.1.6. 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 homogenous dispersion as it causes an upset of the intermolecular force, decreasing the cluster formation of nanoparticles into the base fluid (Mahbubul *et al*.,2017).

3.1.7. 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 nanoparticles.

3.1.8. 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.

3.2. Chemical method of synthesis

The chemical method of synthesis is a bottom-up approach that produces nanoparticles (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 nanoparticles (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:

3.2.1. 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.*, 2017). Chemical reduction is an effective wet-chemical procedure for generating zero-valent nanoparticles from chemically reduced aqueous metal salts, such as silver nitrate, in the case of Ag NP manufacture (Nam & 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).

3.2.2. 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 by hydrolysis. This technique has 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).

3.2.3. Co-precipitation: Coprecipitation 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.

3.2.4. 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 *et al*., 2010). NPs with distinct characteristics are created by altering the temperature of the substrate, the material's composition, and the experimental setup.

3.2.5. Flame spray pyrolysis: This could be altered via flame spray pyrolysis, which can be utilized to create nearly all elemental multicomponent nanoparticles from solvents and affordable solid and liquid precursors. Currently, functionalized cobalt nanoparticles 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).

3.2.6. Spinning: Spinning is an alternative method for producing nanoparticles, mostly used for Tio_2 (Muhammmadi *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—is pushed in (Ealia & Saravanakumar, 2017).

3.3. 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 (fungus, yeast, algae, viruses, bacteria) and other plant components, can be utilized for this process (Figure 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 nanoparticles (Zhang *et al.*, 2020). Metal nanoparticles 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.*,2020). Alkaloids, polyphenols, proteins, reducing sugars, and flavonoids are examples of biomaterials that serve as capping and reducing agents for forming nanoparticles (NPs) from their metal salt precursors (Kuppusamy *et al*.,2016). Metal nanoparticles 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) (Figure 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 nanoparticles (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 nanoparticles 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.*,2020) (Figure 3). Metal nanoparticles synthesized from biological sources (fungi, bacteria, plants) are shown in Table 3.

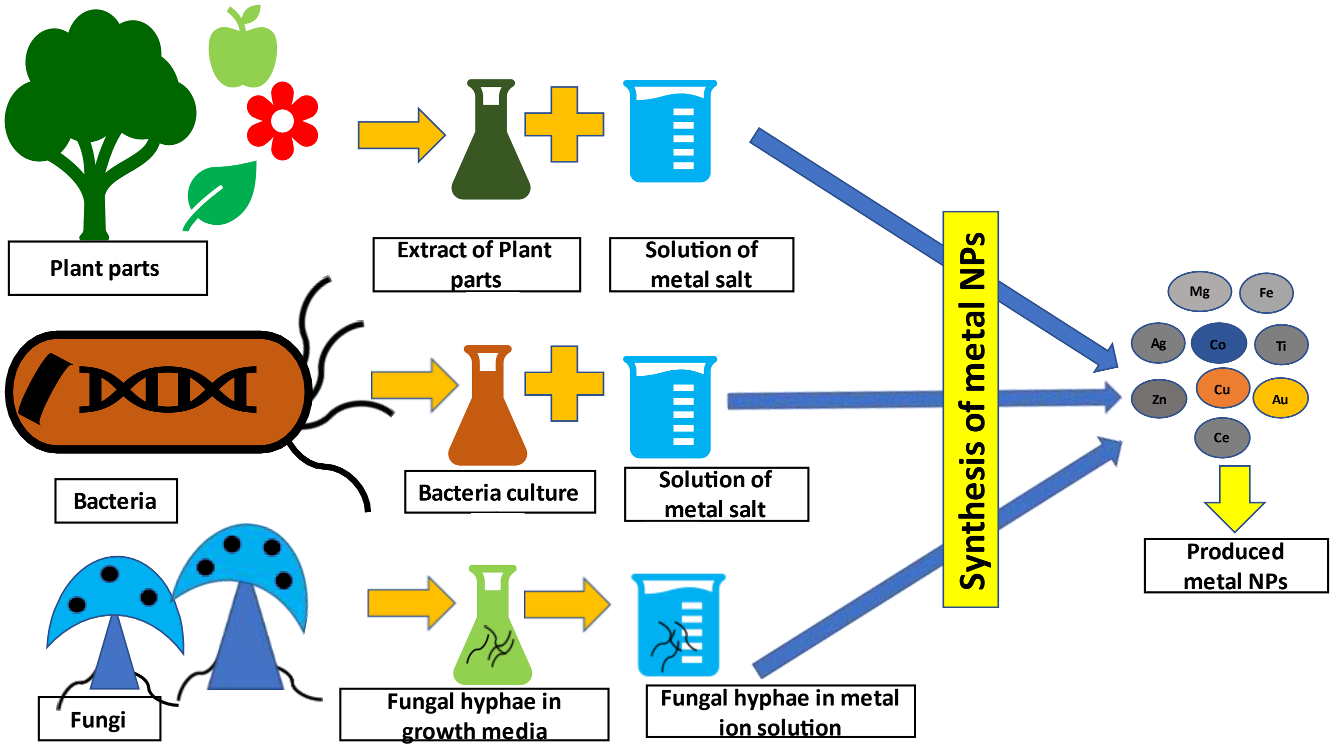

Figure 3. Green synthesis process of metal nanoparticles.

Table 3: Metal NPs and their biological source of synthesis.

Name of metal nanoparticles	**Synthesized from**	**Size**	**References**
	Fungi: • *Ganoderma lucidum* • *Piriformospora indica* • *Penicillium oxalicum*	• 15-22 nm • 1-30 nm • 25-67 nm	Aygün *et al.*,2020; Aziz *et al.*,2019; Feroze *et al.*,2020
	Bacteria: • *Streptomyces olivaceus*	• 12-20 nm	Sanjivkumar *et al.*, 2019; Gomaa, 2019

Silver	(MSU3) - *Lactobacillus paracasei*	- 8-26 nm	
	Plant: - *Prosopis farcta* (fruit) - *Tropaeolum majus L.* - *Piper longum L.* - *Holoptelea integrifolia* - *Camellia Sinensis*	- 11-15 nm - 38-82 nm - 28.8 nm - 32-38 nm - 4-50 nm	Salari *et al.*,2019; Valsalam *et al.*,2019; Yadav *et al.*,2019; Kumar et al.,2019; Rolim *et al.*,2019
Zinc oxide	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	Rehman *et al.*,2019; Jayabalan *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	Sukri *et al.*,2019; Sharmila *et al.*,2019; Khan et al.,2019; Nemati *et al.*,2019

Titanium dioxide	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	Amanulla et al.,2019; Ullah *et al.*,2019; Hameed *et al.*,2019
Iron oxides	Plant: • *Ruellia tuberosa* • *Platanus orientalis* • *Moringa oleifera*	• 20-80 nm • 38 nm • 15-21 nm	Vasantharaj *et al.*,2019; Devi *et al.*,2019; Aisida *et al.*,2020
	Bacteria • *Streptomyces* spp.	• 65-86 nm	Rajeswaran *et al.*,2020
Copper oxide	Plant: • *Moringa oleifera* • *Ruellia tuberosa* • *Ocimum tenuiflorum*	• 35-95 nm • 83.23 nm • 20-30 nm	Dabhane, 2019; Vasantharaj *et al.*,2019; Joshi *et al.*,2019
Gold	Fungi: • *Fusarium solani*	• 40-45 nm	Clarance *et al.*,2020
	Bacteria: • *Lactobacillus casei*	• 7-56 nm	Kikuchi *et al.*,2016
	Plant: • *Anacardium occidentale*	• 10-60 nm	Sunderam *et al.*,2019

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).

4. Impacts of the MNs on plants

4.1. Supply plants with nutrients

Metal Nanoparticles reduce nutrient loss, which improves nutrient uptake, nutrient efficiency, and crop yield through utilizing Nanoparticles as nanofertilizers in agriculture. The chemical fertilizer requirement is decreased day by day using metal nanoparticles. Nanoparticles have a long-term effect on the ecosystem and agricultural soil health (Kumar et al., 2022). Various application methods of nanofertilizer 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 & Kuma, 2019). ZnO nanofertilizer 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 nanoparticles (Table 4). Seed priming shows a greater improvement in germination and other growth parameter in pearl millet by using ZnO Nanoparticles (Kumar et al., 2024). Through seed priming, ZnO Nanoparticles also increased the percentage of germination in 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).

Nanoparticles can enter a plant through stomata or other above-ground parts during foliar spraying. When soil application is followed, Nanoparticles 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 Nanoparticles (Singh et al., 2020; Al-Mamun et al., 2021). The diameter and concentration of the Nanoparticles play important roles (Abd-Alla et al., 2016; Pedruzzi et al., 2020). Two types of pathways, apoplastic and symplastic, are used in the absorption of Nanoparticles. 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 isn't sufficient evidence in favor of the Nanoparticles' following phloem transport pathway in plants. The dimension of the Nanoparticles impacts the uptake. Nanoparticles are required to overcome a lot of physiological root barriers, like the cortex, epidermis, surface cuticle, and casparian strip (Lv et al., 2019). Conversely, Nanoparticles supplied through soil application can reach the plant through the apoplast and symplast both routes (Pérez-de-Luque et al., 2017). Nanoparticles 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 Nanoparticles as nutrient delivery in agriculture are given in Table 4.

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

Nanoparticles	**Crop**	**Method of application**	**Effect**	**Sources**
Ni	Bean	foliar	Ni content increased, whereas Mn, Fe, Cu, and Zn levels decreased. Showed positive effects on physiological characteristics.	Qadir et al., 2024
ZnO	Potato	-	Increased the tuber quality and Zn content but reduced the total number	Zhang et al., 2024

			of potato tuber.	
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 et al., 2018

4.2. Used to control the target pest

Metal nanoparticles (Nanoparticles) offer significant benefits throughout all agricultural stages. Additionally, the development of nanopesticide using Nanoparticles is very efficient compared to conventional fertilizers (Harish, et al., 2022). One major benefit of Nanoparticles is their minuscule size. Nanoparticles 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 nanopesticides minimize loss and adverse effects, the use of nanoparticles 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 Nanoparticles 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 nanoparticles (Nanoparticles) 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 nanopesticide. 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 nanoparticles. Pathogens and antibacterial systems interact directly (Li et al., 2023). Metal nanoparticles 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 nanoparticles 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 nanoparticles, enhancing the insecticide's anti-mealybug efficacy (Zaheer et al., 2022). Ag Nanoparticles saturated with carbons were found to cause harm to internal cellular tissues and the skin in another investigation (Sultana et al., 2018). Ag nanoparticles 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 et al., 2019).

Zinc Nanoparticles 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-nanoparticles 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-nanoparticles are a great approach to protecting food from bacterial diseases in the food sector (Pavic et al., 2022; Dominic et al., 2022). Trypsin inhibitors such as gold-nanoparticles can impede the growth and reproduction of insects. There is little information available about how Nanoparticles affect insects and mites (Chaud et al., 2021). Plants respond better when Nanoparticles are used in addition to other nanoparticles or other composite materials (Table 5). However, there is much potential for employing Nanoparticles as nanopesticides, further research is still necessary to fill the knowledge gap.

Table 5: Potentiality of Nanoparticles used as nanopesticide in crops.

Nanoparticles	**Pest**	**Impact**	**Sources**

ZnO	Mealybug (*Puto barberi*)	Showed 55% effectiveness on the pest population.	(Agredo-Gomez et al., 2024)
Cu-Ag	Thrips	Found effective in the trips infestation. Also enhanced the chlorophyll content and antioxidant activity in the crop.	(Mawale et al., 2024)
Cu-doped ZnO-Nanoparticles	*Spodoptera littoralis*	Showed a 95% reduction in the pest population. Cost-effective & Environment friendly.	(El-Latef et al., 2023)
ZnO Nanoparticles + thiamethoxam nanocomposite	*Spodoptera litura*	Increased the mortality of larvae and reduced the fertility rate.	(Jameel et al., 2020)
(ZnO +TiO2) Nanoparticles	*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 Nanoparticles	*Spodoptera frugiperda*	Increased the antifeedant activity in larva and proved as environment-friendly method.	(Rahman et al,.2022)
Cu Nanoparticles	*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 Nanoparticles	*Tuta absoluta*	Showed a 50% mortality rate in the pest. Proven as beneficial for agriculture.	(Ramkuma et al. 2021)
TD Nanoparticles	*Helicoverpa armigera*	Act as an inhibitor to the development of the pest.	(Chinnaperuma et al., 2018)

4.3. Effects on Improving plant growth and stress tolerance

Nanoparticles 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 nanoparticles 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 nanoparticles. One category provides essential microelements to plants. Among them, copper (Cu), nickel (Ni), iron (Fe), and zinc (Zn) nanoparticles 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 (Faizan *et al.*, 2018; Reddy 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) nanoparticles 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 nanoparticles, such as gold (Au), selenium (Se), cerium (Ce), silicon (Si), and aluminum (Al) nanoparticles, are also utilized, but to a lesser degree. These nanoparticles have beneficial effects on specific plants and can raise the yield or safety of agricultural products (Santás-Miguel *et al.*, 2023).

The concept of 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 nanoparticles (Hoang *et al.*, 2019). Two varieties of metallic nanoparticles 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 ai.*, 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 and also yield, yield quality, freshness and shelf life are positively affected by nanoparticles (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 (Faizan *et al.*, 2018); increased root length, lateral roots and plant height in larch by SiO_2 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, nanoparticles 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, nanoparticles 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.*, 2021)

Nanoparticles (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.*, 2021). The toxic impacts of salt stress on diverse plant species were successfully minimized through the utilization of the following nanoparticles: iron (Fe), potassium (K), copper (Cu), titanium (Ti), carbon (C), zinc (Zn), cerium (Ce), silver (Ag), manganese (Mn), and silicon dioxide (SiO_2) (Zulfiqar & Ashraf, 2021). The implementation of nanoparticles in different concentrations to alleviate the consequences of thermal stress led to improved plant development and hydration (Ali *et al.*, 2021). According to Ahmed *et al.,* In plants impacted by heavy metals, nanoparticles (NPs) provide membrane stability and increase the rate of photosynthesis and chloroplast pigmentation (Ahmed *et al.,* 2021).

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 nanoparticles (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).

4.4. 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 nanoparticles functionalized with ssDNA through colorimetry mechanism (Khaledian et al., 2017). Uses of gold nanoparticles also includes the detection of sweet corn infection with the gram-negative bacteria *Pantoea Stewartii sbusp. Stewartia* (Zhao et al., 2014). Besides, silver and zinc oxide nanoparticles 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 electrochemistry mechanism which is done by nano titanium dioxide (Kumaravel et al., 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 nanoparticles (concentrations @10, 20, 50,100, and 200 mg L^{-1}) enhances the seed germination rate of rice (Wu et al.,2020). Besides, they also enhance the seedling growth of fragrant rice varieties in cadmium stress (Li et al.,2021). Silver nanoparticles 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 mg L-1, Titanium dioxide nanoparticles enhance primed wheat seed germination in drought stress (Faraji et al.,2018) and also in cadmium stress (Faraji and Sepehri, 2019).

5. Harmful/Negative effects of using metal nanoparticles

Agricultural practices can employ metallic nanoparticles 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 nanoparticles can be employed to address the contamination of both water and soil resulting from farming activities (Spanos *et al.*, 2021). In agriculture, nanoparticles 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 nanoparticles 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 nanoparticles, 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 (Sun *et al.*, 2022; Li *et al.*, 2022; Liu *et al.*, 2022). Comprehending these variables is crucial in evaluating the possible hazards associated with the utilization of nanoparticles in agriculture (Balusamy *et al.*, 2023).

Although the precise processes of nanoparticle toxicity remain unclear, researchers have documented that the harmful effects of nanoparticles 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 nanoparticles, 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 *et al.*, 2017; Lian *et al.*, 2020).

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 nanoparticles (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.*, 2017). Once absorbed by plants, nanoparticles (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. (Scherer *et al.*, 2019; Khan *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 nanoparticles can be summed up as: silver nanoparticles (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 (He *et al.*, 2021; Feregrino-Perez *et al.*, 2023); suppressed microbial symbiosis in the vicinity of plant roots of rice by TiO_2 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).

Metal nanoparticles 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 microbiological functions, including the synthesis of organic matter, chemical mineralization, and nutrition cycling (da Silva Júnior *et al.*, 2022). Besides, conventional NPs are produced in ways that are both environmentally damaging and expensive (Saritha *et al.*, 2022; Jiang *et al.*, 2022). On the other hand, numerous investigations also demonstrated that plant-mediated nanoparticles have little to no ecotoxicity toward plants in general (Plachtová *et al.*, 2018).

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 nanoparticles, scientists have coated them with various moieties; nevertheless, as of right now, no thorough study that addresses the long- and short-term impacts of nanoparticles 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 nanoparticles and plants interact in agricultural applications (Shukla *et al.*, 2024). Despite all these reservations, nanoparticles hold immense promise as an emerging technology in agriculture (Balusamy *et al.*, 2023).

6. Future perspectives

The significant hazards to the environment and human health have caused researchers to refocus their efforts on biologically derived metal nanoparticles (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 as nanopesticides, nanoherbicides, nanofertilizers, nanoplant growth promoters, and nanonutrient transporters (Hossain et al.,2023). Metal nanoparticles can improve the whole process from seed germination to yield along with food quality. Including appropriate size and dose, metal nanoparticles 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 nanoparticles 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 nanoparticles 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 nanoparticles can be more effective for plants and lead to sustainable agriculture. At the matured level and pre-harvest conditions, these metal nanoparticles 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 nanoparticles will be used in every agricultural sector to produce food and feed the hidden hunger all over the world. This will contribute to achieving SDG (Sustainable Development Goals). Metal nanoparticles 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 nanoparticles 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 nanoparticles 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.

7. Conclusion

Despite the unexpected consequences, negative environmental impact, and toxicity sometimes, metal nanoparticles have a positive and significant impact, including growth promotion, stress mitigation, yield enhancement, etc., on the plant's life cycle. Thus, metal nanoparticles have become a promising topic that leads to precision and sustainable agriculture. Besides, the green synthesis method of metal nanoparticles 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 nanoparticles in an appropriate size and in an ethical manner. As there is much ongoing research on metal nanoparticles in agricultural sectors all over the world, the researchers should focus on the mitigation of risk factors for metal nanoparticles. They should try to ensure a better outcome in the future.

References

Aashritha, S. (2013). Synthesis of silver nanoparticles by chemical reduction method and their antifungal activity. International research journal of pharmacy, 4(10), 111-113.

Abd El-Latef, E. A., Wahba, M. N., Mousa, S., El-Bassyouni, G. T., & El-Shamy, A. M. (2023). Cu-doped ZnO-nanoparticles as a novel eco-friendly insecticide for controlling Spodoptera littoralis. Biocatalysis and Agricultural Biotechnology, 52, 102823.

Abdulhameed, M. F., Taha, A. A., & Ismail, R. A. (2021). Improvement of cabbage growth and yield by nanofertilizers and nanoparticles. Environmental Nanotechnology, Monitoring & Management, 15, 100437.

Abegunde, S. M., Idowu, K. S., & Sulaimon, A. O. (2020). Plant-mediated iron nanoparticles and their applications as adsorbents for water treatment–a review. Journal of Chemical Reviews, 2(2), 103-113.

Abinaya, S., Kavitha, H. P., Prakash, M., & Muthukrishnaraj, A. J. S. C. (2021). Green synthesis of magnesium oxide nanoparticles and its applications: A review. Sustainable Chemistry and Pharmacy, 19, 100368.

Adrees, M., Khan, Z. S., Ali, S., Hafeez, M., Khalid, S., ur Rehman, M. Z., ... & Rizwan, M. (2020). Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. Chemosphere, 238, 124681.

Agredo-Gomez, A. D., Molano-Molano, J. A., Portela-Patiño, M. C., & Rodríguez-Páez, J. E. (2024). Use of ZnO nanoparticles as a pesticide: In vitro evaluation of their effect on the phytophagous Puto barberi (mealybug). Nano-Structures & Nano-Objects, 37, 101095.

Ahmed, T., Noman, M., Ijaz, M., Ali, S., Rizwan, M., Ijaz, U., ... & Li, B. (2021). Current trends and future prospective in nanoremediation of heavy metals contaminated soils: A way forward towards sustainable agriculture. Ecotoxicology and Environmental Safety, 227, 112888.

Ahmed, T., Noman, M., Manzoor, N., Shahid, M., Abdullah, M., Ali, L., ... & Li, B. (2021). Nanoparticle-based amelioration of drought stress and cadmium toxicity in rice via triggering the stress responsive genetic mechanisms and nutrient acquisition. Ecotoxicology and Environmental Safety, 209, 111829.

Ahmed, T., Noman, M., Manzoor, N., Shahid, M., Hussaini, K. M., Rizwan, M., ... & Li, B. (2021). Green magnesium oxide nanoparticles-based modulation of cellular oxidative repair mechanisms to reduce arsenic uptake and translocation in rice (Oryza sativa L.) plants. Environmental pollution, 288, 117785.

Ahmed, T., Noman, M., Shahid, M., Shahid, M. S., & Li, B. (2021). Antibacterial potential of green magnesium oxide nanoparticles against rice pathogen Acidovorax oryzae. Materials Letters, 282, 128839.

Aisida, S. O., Madubuonu, N., Alnasir, M. H., Ahmad, I., Botha, S., Maaza, M., & Ezema, F. I. (2020). Biogenic synthesis of iron oxide nanorods using Moringa oleifera leaf extract for antibacterial applications. Applied Nanoscience, 10, 305-315.

Al Jabri, H., Saleem, M. H., Rizwan, M., Hussain, I., Usman, K., & Alsafran, M. (2022). Zinc oxide nanoparticles and their biosynthesis: overview. Life, 12(4), 594.

Alam, M. J., Sultana, F., & Iqbal, M. T. (2015). Potential of iron nanoparticles to increase germination and growth of wheat seedling. Journal of Nanoscience with Advanced Technology, 1(3), 14-20.

Ali, A., Zafar, H., Zia, M., ul Haq, I., Phull, A. R., Ali, J. S., & Hussain, A. (2016). Synthesis, characterization, applications, and challenges of iron oxide nanoparticles. Nanotechnology, science and applications, 49-67.

Ali, S., Mehmood, A., & Khan, N. (2021). Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. Journal of Nanomaterials, 2021, 1-17.

Al-Juthery, H. W., Al-Fadhly, J. T., Ali, E. A. H. M., & Al-Taee, R. A. H. G. (2019). Role of some nanofertilizers and atonikin maximizing for production of hydroponically-grown barley fodder. Int. J. Agric. Stat. Sci, 15, 565-570.

Al-Mamun, M. R., Hasan, M. R., Ahommed, M. S., Bacchu, M. S., Ali, M. R., & Khan, M. Z. H. (2021). Nanofertilizers towards sustainable agriculture and environment. Environmental Technology & Innovation, 23, 101658.

Amanulla, A. M., & Sundaram, R. J. M. T. P. (2019). Green synthesis of TiO2 nanoparticles using orange peel extract for antibacterial, cytotoxicity and humidity sensor applications. Materials Today: Proceedings, 8, 323-331.

Amin, H., Minkina, T., & Kumari, A. (2021, December 18-19). Role of Metal-Based Nanomaterials in Plant Growth [Paper presentation]. International Symposium on Soil Science and Plant Nutrition, Samsun, Turkey.

Amodeo, G., Giacometti, R., Spagnoletti, F., Santagapita, P. R., & Perullini, M. (2022). Eco-friendly routes for obtaining nanoparticles and their application in agro-industry. In Nano-enabled Agrochemicals in Agriculture (pp. 49-62). Academic Press.

AS, A. A., & S, T. (2019). Comparative bioassay of silver nanoparticles and malathion on infestation of red flour beetle, Tribolium castaneum. The Journal of basic and applied zoology, 80, 1-10.

Aslam, A. A., Aslam, M. S., & Aslam, A. A. (2022). An overview on green synthesis of nanoparticles and their advanced applications in sustainable agriculture. International Journal of Applied Chemical and Biological Sciences, 3(2), 70-99.

Avellan, A., Yun, J., Morais, B. P., Clement, E. T., Rodrigues, S. M., & Lowry, G. V. (2021). Critical review: Role of inorganic nanoparticle properties on their foliar uptake and in planta translocation. Environmental science & technology, 55(20), 13417-13431.

Aygün, A., Özdemir, S., Gülcan, M., Cellat, K., & Şen, F. (2020). Synthesis and characterization of Reishi mushroom-mediated green synthesis of silver nanoparticles for the biochemical applications. Journal of pharmaceutical and biomedical analysis, 178, 112970.

Azam, M., Bhatti, H. N., Khan, A., Zafar, L., & Iqbal, M. (2022). Zinc oxide nano-fertilizer application (foliar and soil) effect on the growth, photosynthetic pigments and antioxidant system of maize cultivar. Biocatalysis and Agricultural Biotechnology, 42, 102343.

Aziz, N., Faraz, M., Sherwani, M. A., Fatma, T., & Prasad, R. (2019). Illuminating the anticancerous efficacy of a new fungal chassis for silver nanoparticle synthesis. Frontiers in chemistry, 7, 65.

Baker, S., Kumar, K. M., Santosh, P., Rakshith, D., & Satish, S. (2015). Extracellular synthesis of silver nanoparticles by novel Pseudomonas veronii AS41G inhabiting Annona squamosa L.

and their bactericidal activity. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 136, 1434-1440.

Bakhtiari, M., Moaveni, P., & Sani, B. (2015, January). The effect of iron nanoparticles spraying time and concentration on wheat. In biological forum (Vol. 7, No. 1, p. 679). Research Trend.

Bakshi, M., & Kumar, A. (2021). Copper-based nanoparticles in the soil-plant environment: Assessing their applications, interactions, fate and toxicity. Chemosphere, 281, 130940.

Balashanmugam, P., Balakumaran, M. D., Murugan, R., Dhanapal, K., & Kalaichelvan, P. T. (2016). Phytogenic synthesis of silver nanoparticles, optimization and evaluation of in vitro antifungal activity against human and plant pathogens. Microbiological Research, 192, 52-64.

Balusamy, S. R., Joshi, A. S., Perumalsamy, H., Mijakovic, I., & Singh, P. (2023). Advancing sustainable agriculture: a critical review of smart and eco-friendly nanomaterial applications. *Journal of Nanobiotechnology*, *21*(1), 372.

Bellani, L., Siracusa, G., Giorgetti, L., Di Gregorio, S., Castiglione, M. R., Spanò, C., ... & Tassi, E. (2020). TiO2 nanoparticles in a biosolid-amended soil and their implication in soil nutrients, microorganisms and Pisum sativum nutrition. Ecotoxicology and Environmental Safety, 190, 110095.

Brengi, S. H., Abd Allah, E. M., & Abouelsaad, I. A. (2022). Effect of melatonin or cobalt on growth, yield and physiological responses of cucumber (Cucumis sativus L.) plants under salt stress. Journal of the Saudi Society of Agricultural Sciences, 21(1), 51-60.

Briat, J. F., Dubos, C., & Gaymard, F. (2015). Iron nutrition, biomass production, and plant product quality. Trends in plant science, 20(1), 33-40.

Burketová, L., Martinec, J., Siegel, J., Macůrková, A., Maryška, L., & Valentová, O. (2022). Noble metal nanoparticles in agriculture: impacts on plants, associated microorganisms, and biotechnological practices. *Biotechnology Advances*, *58*, 107929.

Cai, L., Chen, J., Liu, Z., Wang, H., Yang, H., & Ding, W. (2018). Magnesium oxide nanoparticles: effective agricultural antibacterial agent against Ralstonia solanacearum. Frontiers in microbiology, 9, 335574.

Carlsson, J. O., & Martin, P. M. (2010). Chemical vapor deposition. In Handbook of Deposition Technologies for films and coatings (pp. 314-363). William Andrew Publishing.

Chandrika, K. P., Qureshi, A. A., Singh, A., Sarada, C., & Gopalan, B. (2022). Fe and Zn metal nanocitrates as plant nutrients through soil application. ACS omega, 7(49), 45481-45492.

Chaud, M., Souto, E. B., Zielinska, A., Severino, P., Batain, F., Oliveira-Junior, J., & Alves, T. (2021). Nanopesticides in agriculture: Benefits and challenge in agricultural productivity, toxicological risks to human health and environment. Toxics, 9(6), 131.

Chen, J., Liu, B., Yang, Z., Qu, J., Xun, H., Dou, R., ... & Wang, L. (2018). Phenotypic, transcriptional, physiological and metabolic responses to carbon nanodot exposure in Arabidopsis thaliana (L.). *Environmental Science: Nano*, *5*(11), 2672-2685.

Chen, X., & Mao, S. S. (2007). Titanium dioxide nanomaterials: synthesis, properties, modifications, and applications. Chemical reviews, 107(7), 2891-2959.

Chinnaperumal, K., Govindasamy, B., Paramasivam, D., Dilipkumar, A., Dhayalan, A., Vadivel, A., ... & Pachiappan, P. (2018). Bio-pesticidal effects of Trichoderma viride formulated titanium dioxide nanoparticle and their physiological and biochemical changes on Helicoverpa armigera (Hub.). Pesticide biochemistry and physiology, 149, 26-36.

Clarance, P., Luvankar, B., Sales, J., Khusro, A., Agastian, P., Tack, J. C., ... & Kim, H. J. (2020). Green synthesis and characterization of gold nanoparticles using endophytic fungi Fusarium solani and its in-vitro anticancer and biomedical applications. Saudi Journal of Biological Sciences, 27(2), 706-712.

da Silva Júnior, A. H., Mulinari, J., de Oliveira, P. V., de Oliveira, C. R. S., & Júnior, F. W. R. (2022). Impacts of metallic nanoparticles application on the agricultural soils microbiota. *Journal of Hazardous Materials Advances*, *7*, 100103.

Dabhane, H. (2019). Antifungal activity of biosynthesized CuO nanoparticles using leaves extract of Moringa oleifera and their structural characterizations.

Dağhan, H. A. T. İ. C. E. (2018). Effects of TiO2 nanoparticles on maize (Zea mays L.) growth, chlorophyll content and nutrient uptake. Applied Ecology and Environmental Research, 16.

Das, V. L., Thomas, R., Varghese, R. T., Soniya, E. V., Mathew, J., & Radhakrishnan, E. K. (2014). Extracellular synthesis of silver nanoparticles by the Bacillus strain CS 11 isolated from industrialized area. 3 Biotech, 4, 121-126.

Devi, H. S., Boda, M. A., Shah, M. A., Parveen, S., & Wani, A. H. (2019). Green synthesis of iron oxide nanoparticles using Platanus orientalis leaf extract for antifungal activity. Green Processing and Synthesis, 8(1), 38-45.

Dikshit, P. K., Kumar, J., Das, A. K., Sadhu, S., Sharma, S., Singh, S., ... & Kim, B. S. (2021). Green synthesis of metallic nanoparticles: Applications and limitations. Catalysts, 11(8), 902.

Dimkpa, C. O., Singh, U., Adisa, I. O., Bindraban, P. S., Elmer, W. H., Gardea-Torresdey, J. L., & White, J. C. (2018). Effects of manganese nanoparticle exposure on nutrient acquisition in wheat (Triticum aestivum L.). Agronomy, 8(9), 158.

Din, M. I., & Rehan, R. (2017). Synthesis, characterization, and applications of copper nanoparticles. Analytical Letters, 50(1), 50-62.

Ditta, A., Arshad, M., & Ibrahim, M. (2015). Nanoparticles in sustainable agricultural crop production: applications and perspectives. Nanotechnology and plant sciences: nanoparticles and their impact on plants, 55-75.

Djanaguiraman, M., Nair, R., Giraldo, J. P., & Prasad, P. V. V. (2018). Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. ACS omega, 3(10), 14406-14416.

Dominic, S., Hussain, A. I., Saleem, M. H., Alshaya, H., Jan, B. L., Ali, S., & Wang, X. (2022). Variation in the primary and secondary metabolites, antioxidant and antibacterial potentials of tomatoes, grown in soil blended with different concentration of fly ash. Plants, 11(4), 551.

Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., & Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. Biotechnology reports, 15, 11-23.

Ealia, S. A. M., & Saravanakumar, M. P. (2017, November). A review on the classification, characterisation, synthesis of nanoparticles and their application. In IOP conference series: materials science and engineering (Vol. 263, No. 3, p. 032019). IOP Publishing.

El-Saadony, M. T., Abd El-Hack, M. E., Taha, A. E., Fouda, M. M., Ajarem, J. S., N. Maodaa, S., ... & Elshaer, N. (2020). Ecofriendly synthesis and insecticidal application of copper nanoparticles against the storage pest Tribolium castaneum. Nanomaterials, 10(3), 587.

Faizan, M., Bhat, J. A., El-Serehy, H. A., Moustakas, M., & Ahmad, P. (2022). Magnesium oxide nanoparticles (MgO-NPs) alleviate arsenic toxicity in soybean by modulating photosynthetic function, nutrient uptake and antioxidant potential. Metals, 12(12), 2030.

Faizan, M., Faraz, A., Yusuf, M., Khan, S. T., & Hayat, S. (2018). Zinc oxide nanoparticle-mediated changes in photosynthetic efficiency and antioxidant system of tomato plants. Photosynthetica, 56, 678-686.

Faraji, J., & Sepehri, A. (2019). Ameliorative effects of TiO 2 nanoparticles and sodium nitroprusside on seed germination and seedling growth of wheat under PEG-stimulated drought stress. Journal of Seed Science, 41, 309-317.

Faraji, J., Sepehri, A., & Salcedo-Reyes, J. C. (2018). Titanium dioxide nanoparticles and sodium nitroprusside alleviate the adverse effects of cadmium stress on germination and seedling growth of wheat (Triticum aestivum L.). Universitas Scientiarum, 23(1), 61-87.

Faraz, A., Faizan, M., Fariduddin, Q., & Hayat, S. (2020). Response of titanium nanoparticles to plant growth: agricultural perspectives. Sustainable Agriculture Reviews 41: Nanotechnology for Plant Growth and Development, 101-110.

Fatima, F., Hashim, A., & Anees, S. (2021). Efficacy of nanoparticles as nanofertilizer production: a review. Environmental Science and Pollution Research, 28(2), 1292-1303.

Feng, Y., Kreslavski, V. D., Shmarev, A. N., Ivanov, A. A., Zharmukhamedov, S. K., Kosobryukhov, A., ... & Shabala, S. (2022). Effects of iron oxide nanoparticles (Fe3O4) on growth, photosynthesis, antioxidant activity and distribution of mineral elements in wheat (Triticum aestivum) Plants. Plants, 11(14), 1894.

Feregrino-Perez, A. A., Dávila, S. M., … & Escalante, K. E. (2023). Toxic Effects of Nanomaterials on Plant Cellular Mechanisms. In *Nanomaterial Interactions with Plant Cellular Mechanisms and Macromolecules and Agricultural Implications* (pp.171-209). Springer.

Fernandes, M., RB Singh, K., Sarkar, T., Singh, P., & Pratap Singh, R. (2020). Recent applications of magnesium oxide (MgO) nanoparticles in various domains. Advanced Materials Letters, 11(8), 1-10.

Feroze, N., Arshad, B., Younas, M., Afridi, M. I., Saqib, S., & Ayaz, A. (2020). Fungal mediated synthesis of silver nanoparticles and evaluation of antibacterial activity. Microscopy Research and Technique, 83(1), 72-80.

Galatage, S. T., Hebalkar, A. S., Dhobale, S. V., Mali, O. R., Kumbhar, P. S., Nikade, S. V., & Killedar, S. G. (2021). Silver nanoparticles: properties, synthesis, characterization, applications and future trends. Silver Micro-Nanoparticles—Properties, Synthesis, Characterization, and Applications.

Gao, M., Chang, J., Wang, Z., Zhang, H., & Wang, T. (2023). Advances in transport and toxicity of nanoparticles in plants. *Journal of Nanobiotechnology, 21*(1), 75.

Ghosh, I., Sadhu, A., Moriyasu, Y., Bandyopadhyay, M., & Mukherjee, A. (2019). Manganese oxide nanoparticles induce genotoxicity and DNA hypomethylation in the moss Physcomitrella patens. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, *842*, 146-157.

Gomaa, E. Z. (2019). Synergistic antibacterial efficiency of bacteriocin and silver nanoparticles produced by probiotic Lactobacillus paracasei against multidrug resistant bacteria. International Journal of Peptide Research and Therapeutics, 25, 1113-1125.

Gröhn, A. J., Pratsinis, S. E., Sánchez-Ferrer, A., Mezzenga, R., & Wegner, K. (2014). Scale-up of nanoparticle synthesis by flame spray pyrolysis: the high-temperature particle residence time. Industrial & Engineering Chemistry Research, 53(26), 10734-10742.

Gutiérrez-Ramírez, J. A., Betancourt-Galindo, R., Aguirre-Uribe, L. A., Cerna-Chávez, E., Sandoval-Rangel, A., Ángel, E. C. D., ... & Hernández-Juárez, A. (2021). Insecticidal effect of zinc oxide and titanium dioxide nanoparticles against Bactericera cockerelli Sulc.(Hemiptera: Triozidae) on tomato Solanum lycopersicum. Agronomy, 11(8), 1460.

GUTIÉRREZ-RUELAS, N. J. ., PALACIO-MÁRQUEZ, A. ., SÁNCHEZ, E., MUÑOZ-MÁRQUEZ, E. ., CHÁVEZ-MENDOZA, C. ., OJEDA-BARRIOS, D. L. ., & FLORES-

CÓRDOVA, M. A. . (2021). Impact of the foliar application of nanoparticles, sulfate and iron chelate on the growth, yield and nitrogen assimilation in green beans. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 49(3), 12437. https://doi.org/10.15835/nbha49312437

Habib, M., Fatima, H., Anwar, T., Qureshi, H., Aisida, S. O., Ahmad, I., ... & Kamal, A. (2024). Green synthesis, characterization, and application of iron and molybdenum nanoparticles and their composites for enhancing the growth of Solanum lycopersicum. Open Chemistry, 22(1), 20230196.

Hameed, R. S., Fayyad, R. J., Nuaman, R. S., Hamdan, N. T., & Maliki, S. A. (2019). Synthesis and characterization of a novel titanium nanoparticals using banana peel extract and investigate its antibacterial and insecticidal activity. J. Pure Appl. Microbiol, 13(4), 2241-2249.

Harish V, Tewari D, Gaur M, Yadav AB, Swaroop S, Bechelany M, Barhoum A (2022) Review on nanoparticles and Nanostructured materials: Bioimaging, Biosensing, Drug Delivery, tissue Engineering, Antimicrobial, and Agro-Food Applications. Nanomaterials 12:457. https://doi.org/10.3390/nano12030457

Haydar, M. S., Ghosh, S., & Mandal, P. (2021). Application of iron oxide nanoparticles as micronutrient fertilizer in mulberry propagation. Journal of Plant Growth Regulation, 1-21.

Hazarika, A., Yadav, M., Yadav, D. K., & Yadav, H. S. (2022). An overview of the role of nanoparticles in sustainable agriculture. Biocatalysis and Agricultural Biotechnology, 43, 102399.

He, A., Jiang, J., Ding, J., & Sheng, G. D. (2021). Blocking effect of fullerene nanoparticles (nC60) on the plant cell structure and its phytotoxicity. *Chemosphere*, *278*, 130474.

Hoang, S. A., Nguyen, L. Q., Nguyen, N. H., Tran, C. Q., Nguyen, D. V., Le, N. T., ... & Phan, C. M. (2019). Metal nanoparticles as effective promotors for Maize production. Scientific reports, 9(1), 13925.

Hojjat, S. S., & Ganjali, A. (2016). The effect of silver nanoparticle on lentil seed germination under drought stress. Int J Farm Allied Sci, 5(3), 208-212.

Hojjat, S. S., & Kamyab, M. (2017). The effect of silver nanoparticle on Fenugreek seed germination under salinity levels. Russian agricultural sciences, 43, 61-65.

Hong, J., Wang, C., Wagner, D. C., Gardea-Torresdey, J. L., He, F., & Rico, C. M. (2021). Foliar application of nanoparticles: mechanisms of absorption, transfer, and multiple impacts. Environmental Science: Nano, 8(5), 1196-1210.

Hossain, M. E., Saha, P., & Bezbaruah, A. N. (2023). Environmentally Benign Synthesis of Metal Nanoparticles for Fertilizer Applications in Agriculture. In Nanofertilizers for Sustainable Agroecosystems: Recent Advances and Future Trends (pp. 125-150). Cham: Springer Nature Switzerland.

Hossain, M. E., Saha, P., & Bezbaruah, A. N. (2023). Environmentally Benign Synthesis of Metal Nanoparticles for Fertilizer Applications in Agriculture. In Nanofertilizers for Sustainable Agroecosystems: Recent Advances and Future Trends (pp. 125-150). Cham: Springer Nature Switzerland.

Hu, J., Wu, X., Wu, F., Chen, W., Zhang, X., White, J. C., ... & Wang, X. (2020). TiO 2 nanoparticle exposure on lettuce (Lactuca sativa L.): Dose-dependent deterioration of nutritional quality. Environmental Science: Nano, 7(2), 501-513.

Husen, A. (2017). Gold nanoparticles from plant system: synthesis, characterization and their application. Nanoscience and plant–soil systems, 455-479.

Ijaz, I., Gilani, E., Nazir, A., & Bukhari, A. (2020). Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. Green Chemistry Letters and Reviews, 13(3), 223-245.

Iqbal, S., Waheed, Z., & Naseem, A. (2020). Nanotechnology and abiotic stresses. Nanoagronomy, 37-52.

Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. Green chemistry, 13(10), 2638-2650.

Iravani, S., Korbekandi, H., Mirmohammadi, S. V., & Zolfaghari, B. (2014). Synthesis of silver nanoparticles: chemical, physical and biological methods. Research in pharmaceutical sciences, 9(6), 385-406.

Jahani, M., Khavari-Nejad, R. A., Mahmoodzadeh, H., & Saadatmand, S. (2020). Effects of cobalt oxide nanoparticles (Co3O4 NPs) on ion leakage, total phenol, antioxidant enzymes activities and cobalt accumulation in Brassica napus L. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 48(3), 1260-1275.

Jameel, M., Shoeb, M., Khan, M. T., Ullah, R., Mobin, M., Farooqi, M. K., & Adnan, S. M. (2020). Enhanced insecticidal activity of thiamethoxam by zinc oxide nanoparticles: A novel nanotechnology approach for pest control. ACS omega, 5(3), 1607-1615.

Jamkhande, P. G., Ghule, N. W., Bamer, A. H., & Kalaskar, M. G. (2019). Metal nanoparticles synthesis: An overview on methods of preparation, advantages and disadvantages, and applications. Journal of drug delivery science and technology, 53, 101174.

Javed, A., Ali, E., Afzal, K. B., Osman, A., & Riaz, S. (2022). Soil fertility: Factors affecting soil fertility, and biodiversity responsible for soil fertility. International Journal of Plant, Animal and Environmental Sciences, 12(1), 21-33.

Jayabalan, J., Mani, G., Krishnan, N., Pernabas, J., Devadoss, J. M., & Jang, H. T. (2019). Green biogenic synthesis of zinc oxide nanoparticles using Pseudomonas putida culture and its In vitro antibacterial and anti-biofilm activity. Biocatalysis and Agricultural Biotechnology, 21, 101327.

Jhanzab, H. M., Razzaq, A., Bibi, Y., Yasmeen, F., Yamaguchi, H., Hitachi, K., ... & Komatsu, S. (2019). Proteomic analysis of the effect of inorganic and organic chemicals on silver nanoparticles in wheat. International journal of molecular sciences, 20(4), 825.

Jiang, Y., Zhou, P., Zhang, P., Adeel, M., Shakoor, N., Li, Y., ... & Rui, Y. (2022). Green synthesis of metal-based nanoparticles for sustainable agriculture. Environmental Pollution, 309, 119755.

Johnson, M. S., Sajeev, S., & Nair, R. S. (2021, March). Role of Nanosensors in agriculture. In 2021 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE) (pp. 58-63). IEEE.

Joshi, N. C., & Prakash, Y. A. S. H. W. A. N. I. (2019). Leaves extract-based biogenic synthesis of cupric oxide nanoparticles, characterizations, and antimicrobial activity. Asian J. Pharm. Clin. Res, 12, 288-291.

Judy, J. D., Unrine, J. M., & Bertsch, P. M. (2011). Evidence for biomagnification of gold nanoparticles within a terrestrial food chain. *Environmental science & technology*, *45*(2), 776-781.

Jurkow, R., Pokluda, R., Sękara, A., & Kalisz, A. (2020). Impact of foliar application of some metal nanoparticles on antioxidant system in oakleaf lettuce seedlings. BMC plant biology, 20, 1-12.

Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. Nature nanotechnology, 14(6), 532–540. https://doi.org/10.1038/s41565-019-0439-5

Kale, S. K., Parishwad, G. V., & Patil, A. S. H. A. S. (2021). Emerging agriculture applications of silver nanoparticles. ES Food & Agroforestry, 3, 17-22.

Kalia, A., Abd-Elsalam, K. A., & Kuca, K. (2020). Zinc-based nanomaterials for diagnosis and management of plant diseases: Ecological safety and future prospects. Journal of fungi, 6(4), 222.

Kalimuthu, K., Babu, R. S., Venkataraman, D., Bilal, M., & Gurunathan, S. (2008). Biosynthesis of silver nanocrystals by Bacillus licheniformis. Colloids and surfaces B: Biointerfaces, 65(1), 150-153.

Kamal, A., Saleem, M. H., Alshaya, H., Okla, M. K., Chaudhary, H. J., & Munis, M. F. H. (2022). Ball-milled synthesis of maize biochar-ZnO nanocomposite (MB-ZnO) and estimation of its photocatalytic ability against different organic and inorganic pollutants. Journal of Saudi Chemical Society, 26(3), 101445.

Kandhol, N., Singh, V. P., Ramawat, N., Prasad, R., Chauhan, D. K., Sharma, S., ... & Tripathi, D. K. (2022). Nano-priming: Impression on the beginner of plant life. Plant Stress, 5, 100091.

Kaningini, A. G., Nelwamondo, A. M., Azizi, S., Maaza, M., & Mohale, K. C. (2022). Metal nanoparticles in agriculture: A review of possible use. Coatings, 12(10), 1586.

Kasana, R. C., Panwar, N. R., Kaul, R. K., & Kumar, P. (2016). Copper nanoparticles in agriculture: biological synthesis and antimicrobial activity. Nanoscience in Food and Agriculture 3, 129-143.

Keerthana, P., Vijayakumar, S., Vidhya, E. V. N. P., Punitha, V. N., Nilavukkarasi, M., & Praseetha, P. K. (2021). Biogenesis of ZnO nanoparticles for revolutionizing agriculture: A step towards anti-infection and growth promotion in plants. Industrial Crops and Products, 170, 113762.

Khaledian, S., Nikkhah, M., Shams-bakhsh, M., & Hoseinzadeh, S. (2017). A sensitive biosensor based on gold nanoparticles to detect Ralstonia solanacearum in soil. Journal of General Plant Pathology, 83, 231-239.

Khan, A. R., Wakeel, A., Muhammad, N., Liu, B., Wu, M., Liu, Y., … & Gan, Y. (2019). Involvement of ethylene signaling in zinc oxide nanoparticle-mediated biochemical changes in Arabidopsis thaliana leaves. *Environmental Science: Nano*, *6*(1), 341-355.

Khan, A. U., Khan, M., Khan, A. A., Parveen, A., Ansari, S., & Alam, M. (2022). Effect of phyto-assisted synthesis of magnesium oxide nanoparticles (MgO-NPs) on bacteria and the root-knot nematode. Bioinorganic Chemistry and Applications, 2022.

Khan, M., Khan, M. S. A., Borah K. K., Goswami, Y., … & Chakrabartty, I. (2021). The potential exposure and hazards of metal-based nanoparticles on plants and environment: A review. *Environmental Advances*, *6*(80), 100128.

Khan, S., Khan, R. S., Zahoor, M., Islam, N. U., Khan, T., Muhammad, Z., ... & Bari, A. (2023). Alnus nitida and urea-doped Alnus nitida-based silver nanoparticles synthesis, characterization, their effects on the biomass and elicitation of secondary metabolites in wheat seeds under in vitro conditions. Heliyon, 9(3).

Khan, S., Sher Khan, R., Khalid, A., Gul, M., Brekhna, Wadood, A., ... & Ullah, R. (2024). Biomedical and agricultural applications of gold nanoparticles (AuNPs): a comprehensive review. Zeitschrift für Physikalische Chemie, (0).

Khan, S., Zahoor, M., Khan, R. S., Ikram, M., & Islam, N. U. (2023). The impact of silver nanoparticles on the growth of plants: The agriculture applications. Heliyon.

Khan, Z. U. H., Sadiq, H. M., Shah, N. S., Khan, A. U., Muhammad, N., Hassan, S. U., ... & Zakir, A. (2019). Greener synthesis of zinc oxide nanoparticles using Trianthema portulacastrum extract and evaluation of its photocatalytic and biological applications. Journal of Photochemistry and Photobiology B: Biology, 192, 147-157.

Kikuchi, F., Kato, Y., Furihata, K., Kogure, T., Imura, Y., Yoshimura, E., & Suzuki, M. (2016). Formation of gold nanoparticles by glycolipids of Lactobacillus casei. Scientific Reports, 6(1), 34626.

Kim, M., Osone, S., Kim, T., Higashi, H., & Seto, T. (2017). Synthesis of nanoparticles by laser ablation: A review. KONA Powder and Particle Journal, 34, 80-90.

Koleva, L., Umar, A., Yasin, N. A., Shah, A. A., Siddiqui, M. H., Alamri, S., ... & Shabbir, Z. (2022). Iron oxide and silicon nanoparticles modulate mineral nutrient homeostasis and metabolism in cadmium-stressed Phaseolus vulgaris. Frontiers in Plant Science, 13, 806781.

Kumar, A., Singh, K., Verma, P., Singh, O., Panwar, A., Singh, T., ... & Raliya, R. (2022). Effect of nitrogen and zinc nanofertilizer with the organic farming practices on cereal and oil seed crops. Scientific reports, 12(1), 6938.

Kumar, R., Dadhich, A., Dhiman, M., Sharma, L., & Sharma, M. M. (2024). Stimulatory effect of ZnO nanoparticles as a nanofertilizer in seed priming of pearl millet (Pennisetum glaucum) and their bioactivity studies. South African Journal of Botany, 165, 30-38.

Kumar, V., Singh, S., Srivastava, B., Bhadouria, R., & Singh, R. (2019). Green synthesis of silver nanoparticles using leaf extract of Holoptelea integrifolia and preliminary investigation of its antioxidant, anti-inflammatory, antidiabetic and antibacterial activities. Journal of Environmental Chemical Engineering, 7(3), 103094.

Kumaravel, A., & Chandrasekaran, M. (2011). A biocompatible nano TiO2/nafion composite modified glassy carbon electrode for the detection of fenitrothion. Journal of electroanalytical chemistry, 650(2), 163-170.

Kumari, S., & Chauhan, S. (2019). A review on applications of metal oxide nanoparticles in agriculture. Int J Conserv Sci, 7, 2143-2146.

Larosi, M. B., García, J. D. V., & Rodríguez, A. R. (2022). Laser synthesis of nanomaterials. Nanomaterials, 12(17), 2903.

Li, J., Wang, C., Yue, L., Chen, F., Cao, X., & Wang, Z. (2022). Nano-QSAR modeling for predicting the cytotoxicity of metallic and metal oxide nanoparticles: A review. *Ecotoxicology and environmental safety*, *243*, 113955. https://doi.org/10.1016/j.ecoenv.2022.113955.

Li, Y., Liang, L., Li, W., Ashraf, U., Ma, L., Tang, X., ... & Mo, Z. (2021). ZnO nanoparticle-based seed priming modulates early growth and enhances physio-biochemical and metabolic profiles of fragrant rice against cadmium toxicity. Journal of Nanobiotechnology, 19, 1-19.

Li, Y., Zhang, P., Li, M., Shakoor, N., Adeel, M., Zhou, P., ... & Rui, Y. (2023). Application and mechanisms of metal-based nanoparticles in the control of bacterial and fungal crop diseases. Pest Management Science, 79(1), 21-36.

Lian, J., Wu, J., Xiong, H., Zeb, A., Yang, T., Su, X., … & Liu, W. (2020). Impact of polystyrene nanoplastics (PSNPs) on seed germination and seedling growth of wheat (Triticum aestivum L.). *Journal of hazardous materials*, *385*, 121620.

Liang, Y., Duan, Y., Fan, C., Dong, H., Yang, J., Tang, J., ... & Cao, Y. (2019). Preparation of kasugamycin conjugation based on ZnO quantum dots for improving its effective utilization. Chemical Engineering Journal, 361, 671-679.

Liman, R., Acikbas, Y., Ciğerci, İ. H., Ali, M. M., & Kars, M. D. (2020). Cytotoxic and Genotoxic Assessment of Silicon Dioxide Nanoparticles by Allium and Comet Tests. *Bulletin of environmental contamination and toxicology*, *104*(2), 215–221. https://doi.org/10.1007/s00128-020-02783-3

Liu, Z., Xu, Z., Xu, L., Buyong, F., Chay, T. C., Li, Z., ... & Wang, X. (2022). Modified biochar: synthesis and mechanism for removal of environmental heavy metals. *Carbon Research*, *1*(1), 8.

Lv, J., Christie, P., and Zhang, S. (2019). Uptake, translocation, and transformationof metal-based nanoparticles in plants: recent advances and methodologicalchallenges. Environ. Sci. Nano 6, 41–59. doi: 10.1039/C8EN00645H

Ma, J., Lü, X., & Huang, Y. (2011). Genomic analysis of cytotoxicity response to nanosilver in human dermal fibroblasts. *Journal of Biomedical Nanotechnology*, *7*(2), 263-275.

Ma, Y., Xie, C., He, X., Zhang, B., Yang, J., Sun, M., ... & Zhang, Z. (2020). Effects of ceria nanoparticles and CeCl3 on plant growth, biological and physiological parameters, and nutritional value of soil grown common bean (Phaseolus vulgaris). Small, 16(21), 1907435.

Mahendran, D., Geetha, N., & Venkatachalam, P. (2019). Role of silver nitrate and silver nanoparticles on tissue culture medium and enhanced the plant growth and development. In vitro Plant Breeding towards Novel Agronomic Traits: Biotic and Abiotic Stress Tolerance, 59-74.

Mahil, E. I. T., & Kumar, B. A. (2019). Foliar application of nanofertilizers in agricultural crops–A review. J. Farm Sci, 32(3), 239-249.

Maity, A., Natarajan, N., Vijay, D., Srinivasan, R., Pastor, M., & Malaviya, D. R. (2018). Influence of metal nanoparticles (NPs) on germination and yield of oat (Avena sativa) and berseem (Trifolium alexandrinum). Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 88, 595-607.

Marslin, G., Sheeba, C. J., & Franklin, G. (2017). Nanoparticles alter secondary metabolism in plants via ROS burst. *Frontiers in plant science, 8,* 257354.

Mathew, S. S., Sunny, N. E., & Shanmugam, V. (2021). Green synthesis of anatase titanium dioxide nanoparticles using Cuminum cyminum seed extract; effect on Mung bean (Vigna radiata) seed germination. Inorganic Chemistry Communications, 126, 108485.

Mawale, K. S., Nandini, B., & Giridhar, P. (2024). Copper and Silver Nanoparticle Seed Priming and Foliar Spray Modulate Plant Growth and Thrips Infestation in Capsicum spp. ACS omega, 9(3), 3430-3444.

Miguel-Rojas, C., & Pérez-de-Luque, A. (2023). Nanobiosensors and nanoformulations in agriculture: new advances and challenges for sustainable agriculture. Emerging Topics in Life Sciences, 7(2), 229-238.

Mishra, S., & Singh, H. B. (2015). Biosynthesized silver nanoparticles as a nanoweapon against phytopathogens: exploring their scope and potential in agriculture. Applied microbiology and biotechnology, 99, 1097-1107.

Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. Frontiers in Nanotechnology, 2, 579954.

Mody, V. V., Siwale, R., Singh, A., & Mody, H. R. (2010). Introduction to metallic nanoparticles. Journal of Pharmacy and bioallied sciences, 2(4), 282-289.

Mohamed, A. A., Fouda, A., Abdel-Rahman, M. A., Hassan, S. E. D., El-Gamal, M. S., Salem, S. S., & Shaheen, T. I. (2019). Fungal strain impacts the shape, bioactivity and multifunctional properties of green synthesized zinc oxide nanoparticles. Biocatalysis and Agricultural Biotechnology, 19, 101103.

Mohammadi, S., Harvey, A., & Boodhoo, K. V. (2014). Synthesis of TiO2 nanoparticles in a spinning disc reactor. Chemical Engineering Journal, 258, 171-184.

Muhammad Abdullah, M. A., Muhammad Numan, M. N., Shafique, M. S., Awais Shakoor, A. S., Shamsur Rehman, S. R., & Ahmad, M. I. (2016). Genetic variability and interrelationship of various agronomic traits using correlation and path analysis in cotton (Gossypium hirsutum L.).

Murthy, H. A., Ayanie, G. T., Zeleke, T. D., Sintayehu, Y. D., & Ravikumar, C. R. (2022). Metal Nanoparticles in Encapsulation and Delivery Systems of Food Ingredients and Nutraceuticals. In Handbook of Nanotechnology in Nutraceuticals (pp. 301-328). CRC Press.

Mutlu, F., Yurekli, F., Mutlu, B., Emre, F. B., Okusluk, F., & Ozgul, O. (2018). Assessment of phytotoxic and genotoxic effects of anatase TiO2 nanoparticles on maize cultivar by using RAPD analysis. *Fresenius Environmental Bulletin*, *27*(1), 436-445.

Nair, P. M. G., & Chung, I. M. (2017). Regulation of morphological, molecular and nutrient status in Arabidopsis thaliana seedlings in response to ZnO nanoparticles and Zn ion exposure. *Science of the Total Environment*, *575*, 187-198.

Nam, N. H., & Luong, N. H. (2019). Nanoparticles: Synthesis and applications. In Materials for biomedical engineering (pp. 211-240). Elsevier.

Namasivayam, S. K. R., Kumar, S., Samrat, K., & Bharani, R. A. (2023). Noteworthy biocompatibility of effective microorganisms (EM) like microbial beneficial culture formulation with metal and metal oxide nanoparticles. Environmental Research, 231, 116150.

Nazarova, A. A. (2022, June). The effect of a mixture of iron and nickel nanopowders of various concentrations on the growth and yield of corn. In IOP Conference Series: Earth and Environmental Science (Vol. 1045, No. 1, p. 012151). IOP Publishing.

Ndaba, B., Roopnarain, A., Haripriya, R. A. M. A., & Maaza, M. (2022). Biosynthesized metallic nanoparticles as fertilizers: An emerging precision agriculture strategy. Journal of Integrative Agriculture, 21(5), 1225-1242.

Nejatzadeh, F. (2021). Effect of silver nanoparticles on salt tolerance of Satureja hortensis l. during in vitro and in vivo germination tests. Heliyon, 7(2).

Nejatzadeh, F. (2021). Effect of silver nanoparticles on salt tolerance of Satureja hortensis l. during in vitro and in vivo germination tests. Heliyon, 7(2).

Nemati, S., Hosseini, H. A., Hashemzadeh, A., Mohajeri, M., Sabouri, Z., Darroudi, M., & Oskuee, R. K. (2019). Cytotoxicity and photocatalytic applications of biosynthesized ZnO nanoparticles by Rheum turketanicum rhizome extract. Materials Research Express, 6(12), 125016.

Nie, D., Li, J., Xie, Q., Ai, L., Zhu, C., Wu, Y., ... & Tan, W. (2023). Nanoparticles: a potential and effective method to control insect-borne diseases. Bioinorganic Chemistry and Applications, 2023.

Nikam, A. V., Prasad, B. L. V., & Kulkarni, A. A. (2018). Wet chemical synthesis of metal oxide nanoparticles: a review. CrystEngComm, 20(35), 5091-5107.

Nile, S. H., Thiruvengadam, M., Wang, Y., Samynathan, R., Shariati, M. A., Rebezov, M., ... & Kai, G. (2022). Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives. Journal of nanobiotechnology, 20(1), 254.

Noha, K., Bondok, A. M., & El-Dougdoug, K. A. (2018). Evaluation of silver nanoparticles as antiviral agent against ToMV and PVY in tomato plants. Sciences, 8(01), 100-111.

Ogunyemi, S. O., Xu, X., Xu, L., Abdallah, Y., Rizwan, M., Lv, L., ... & Li, B. (2023). Cobalt oxide nanoparticles: An effective growth promoter of Arabidopsis plants and nano-pesticide against bacterial leaf blight pathogen in rice. Ecotoxicology and Environmental Safety, 257, 114935.

Ogunyemi, S. O., Xu, X., Xu, L., Abdallah, Y., Rizwan, M., Lv, L., ... & Li, B. (2023). Cobalt oxide nanoparticles: An effective growth promoter of Arabidopsis plants and nano-pesticide against bacterial leaf blight pathogen in rice. Ecotoxicology and Environmental Safety, 257, 114935.

Pan, X., Nie, D., Guo, X., Xu, S., Zhang, D., Cao, F., & Guan, X. (2023). Effective control of the tomato wilt pathogen using TiO 2 nanoparticles as a green nanopesticide. Environmental Science: Nano, 10(5), 1441-1452.

Panpatte, D. G., Jhala, Y. K., Shelat, H. N., & Vyas, R. V. (2016). Nanoparticles: the next generation technology for sustainable agriculture. Microbial Inoculants in Sustainable Agricultural Productivity: Vol. 2: Functional Applications, 289-300.

Panyala, N. R., Peña-Méndez, E. M., & Havel, J. (2008). Silver or silver nanoparticles: a hazardous threat to the environment and human health?. Journal of applied biomedicine, 6(3).

Parashar, M., Shukla, V. K., & Singh, R. (2020). Metal oxides nanoparticles via sol–gel method: a review on synthesis, characterization and applications. Journal of Materials Science: Materials in Electronics, 31(5), 3729-3749.

Pavić, V., Flačer, D., Jakovljević, M., Molnar, M., & Jokić, S. (2019). Assessment of total phenolic content, in vitro antioxidant and antibacterial activity of Ruta graveolens L. extracts obtained by choline chloride based natural deep eutectic solvents. Plants, 8(3), 69.

Pedruzzi, D. P., Araujo, L. O., Falco, W. F., Machado, G., Casagrande, G. A., Colbeck, I., … Caires, A. R. L. (2020). ZnO nanoparticles impact on the photosynthetic activity of Vicia faba: Effect of particle size and concentration. NanoImpact, 100246.

Pérez-de-Luque, A. (2017). Interaction of nanomaterials with plants: what do we need for real applications in agriculture?. Frontiers in Environmental Science, 5, 12.

Plachtová, P., Medrikova, Z., Zboril, R., Tucek, J., Varma, R. S., & Maršálek, B. (2018). Iron and iron oxide nanoparticles synthesized with green tea extract: differences in ecotoxicological profile and ability to degrade malachite green. *ACS sustainable chemistry & engineering*, *6*(7), 8679-8687.

Polischuk, S. D., Churilov, G. I., Borychev, S. N., Byshov, N. V., & Nazarova, A. A. (2018). Nanopowders of cuprum, cobalt and their oxides used in the intensive technology for growing cucumbers. International journal of nanotechnology, 15(4-5), 352-369.

Powers, C. M., Badireddy, A. R., Ryde, I. T., Seidler, F. J., & Slotkin, T. A. (2011). Silver nanoparticles compromise neurodevelopment in PC12 cells: critical contributions of silver ion, particle size, coating, and composition. Environmental health perspectives, 119(1), 37-44.

Prakash, V., Peralta-Videa, J., Tripathi, D. K., Ma, X., & Sharma, S. (2021). Recent insights into the impact, fate and transport of cerium oxide nanoparticles in the plant-soil continuum. Ecotoxicology and environmental safety, 221, 112403.

Prerna, D. I., Govindaraju, K., Tamilselvan, S., Kannan, M., Vasantharaja, R., Chaturvedi, S., & Shkolnik, D. (2021). Influence of nanoscale micro-nutrient α-Fe2O3 on seed germination, seedling growth, translocation, physiological effects and yield of rice (Oryza sativa) and maize (Zea mays). Plant Physiology and Biochemistry, 162, 564-580.

Pullagurala, V. L. R., Adisa, I. O., Rawat, S., Kalagara, S., Hernandez-Viezcas, J. A., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2018). ZnO nanoparticles increase photosynthetic pigments and decrease lipid peroxidation in soil grown cilantro (Coriandrum sativum). Plant physiology and biochemistry, 132, 120-127.

Qadir, S. A., & Fathulla, C. N. (2024). Physiological and anatomical responses of common bean (phaseolus vulgaris l.) to nickle nanoparticles foliar spray. Iraqi Journal of Agricultural Sciences, 55(Special Issue), 80-89.

Qi, M., Liu, Y., & Li, T. (2013). Nano-TiO 2 improve the photosynthesis of tomato leaves under mild heat stress. Biological trace element research, 156, 323-328.

Quaresma, P., Soares, L., Contar, L., Miranda, A., Osório, I., Carvalho, P. A., ... & Pereira, E. (2009). Green photocatalytic synthesis of stable Au and Ag nanoparticles. Green Chemistry, 11(11), 1889-1893.

Rahman, A., Pittarate, S., Perumal, V., Rajula, J., Thungrabeab, M., Mekchay, S., & Krutmuang, P. (2022). Larvicidal and antifeedant effects of copper nano-pesticides against Spodoptera frugiperda (JE Smith) and its immunological response. Insects, 13(11), 1030.

Rai, M., Ingle, A. P., Pandit, R., Paralikar, P., Shende, S., Gupta, I., ... & da Silva, S. S. (2018). Copper and copper nanoparticles: Role in management of insect-pests and pathogenic microbes. Nanotechnology Reviews, 7(4), 303-315.

Rai, V., Acharya, S., & Dey, N. (2012). Implications of nanobiosensors in agriculture.

Raj, S. N., Anooj, E. S., Rajendran, K., & Vallinayagam, S. (2021). A comprehensive review on regulatory invention of nano pesticides in Agricultural nano formulation and food system. Journal of Molecular Structure, 1239, 130517.

Rajan, R., Chandran, K., Harper, S. L., Yun, S. I., & Kalaichelvan, P. T. (2015). Plant extract synthesized silver nanoparticles: An ongoing source of novel biocompatible materials. Industrial Crops and Products, 70, 356-373.

Rajeshkumar, S., & Naik, P. (2018). Synthesis and biomedical applications of cerium oxide nanoparticles–a review. Biotechnology Reports, 17, 1-5.

Rajeswaran, S., Somasundaram Thirugnanasambandan, S., Dewangan, N. K., Moorthy, R. K., Kandasamy, S., & Vilwanathan, R. (2020). Multifarious pharmacological applications of green routed eco-friendly iron nanoparticles synthesized by Streptomyces Sp.(SRT12). Biological trace element research, 194, 273-283.

Rajna, S., Paschapur, A.U. and Raghavendra, K.V. (2019). Nanopesticides: Its scope and

Rajput, N. (2015). Methods of preparation of nanoparticles-a review. International Journal of Advances in Engineering & Technology, 7(6), 1806.

Rajput, N. (2015). Methods of preparation of nanoparticles-a review. International Journal of Advances in Engineering & Technology, 7(6), 1806.

Rajput, V., Minkina, T., Fedorenko, A., Sushkova, S., Mandzhieva, S., Lysenko, V., … & Ghazaryan, K. (2018). Toxicity of copper oxide nanoparticles on spring barley (Hordeum sativum distichum). *Science of the Total Environment*, *645*, 1103-1113.

Raliya, R., Biswas, P., & Tarafdar, J. C. (2015). TiO2 nanoparticle biosynthesis and its physiological effect on mung bean (Vigna radiata L.). Biotechnology Reports, 5, 22-26.

Raliya, R., Saharan, V., Dimkpa, C., & Biswas, P. (2017). Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. Journal of agricultural and food chemistry, 66(26), 6487-6503.

Ramkumar, G., Asokan, R., Ramya, S., & Gayathri, G. (2021). Characterization of Trigonella foenum-graecum derived iron nanoparticles and its potential pesticidal activity against Tuta absoluta (Lepidoptera). Journal of Cluster Science, 32, 1185-1190.

Rane, A. V., Kanny, K., Abitha, V. K., & Thomas, S. (2018). Methods for synthesis of nanoparticles and fabrication of nanocomposites. In Synthesis of inorganic nanomaterials (pp. 121-139). Woodhead publishing.

Rasheed, A., Li, H., Tahir, M. M., Mahmood, A., Nawaz, M., Shah, A. N., ... & Wu, Z. (2022). The role of nanoparticles in plant biochemical, physiological, and molecular responses under drought stress: A review. Frontiers in Plant Science, 13, 976179.

Rehman, S., Jermy, B. R., Akhtar, S., Borgio, J. F., Abdul Azeez, S., Ravinayagam, V., ... & Gani, A. (2019). Isolation and characterization of a novel thermophile; Bacillus haynesii, applied for the green synthesis of ZnO nanoparticles. Artificial Cells, Nanomedicine, and Biotechnology, 47(1), 2072-2082.

Rico, C. M., Lee, S. C., Rubenecia, R., Mukherjee, A., Hong, J., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2014). Cerium oxide nanoparticles impact yield and modify nutritional parameters in wheat (Triticum aestivum L.). Journal of agricultural and food chemistry, 62(40), 9669-9675.

Rico, C. M., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2015). Chemistry, biochemistry of nanoparticles, and their role in antioxidant defense system in plants. *Nanotechnology and plant sciences: nanoparticles and their impact on plants*, 1-17.

Rizwan, M., Ali, S., Ali, B., Adrees, M., Arshad, M., Hussain, A., ... & Waris, A. A. (2019). Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat. Chemosphere, 214, 269-277.

Rizwan, M., Ali, S., Rehman, M. Z. U., & Maqbool, A. (2019). A critical review on the effects of zinc at toxic levels of cadmium in plants. Environmental Science and Pollution Research, 26, 6279-6289.

Rodríguez-González, V., Terashima, C., & Fujishima, A. (2019). Applications of photocatalytic titanium dioxide-based nanomaterials in sustainable agriculture. Journal of Photochemistry and Photobiology C: Photochemistry Reviews, 40, 49-67.

Rolim, W. R., Pelegrino, M. T., de Araújo Lima, B., Ferraz, L. S., Costa, F. N., Bernardes, J. S., ... & Seabra, A. B. (2019). Green tea extract mediated biogenic synthesis of silver nanoparticles: Characterization, cytotoxicity evaluation and antibacterial activity. Applied Surface Science, 463, 66-74.

Rossi, L., Zhang, W., Lombardini, L., & Ma, X. (2016). The impact of cerium oxide nanoparticles on the salt stress responses of Brassica napus L. Environmental Pollution, 219, 28-36.

Rui, M., Ma, C., Hao, Y., Guo, J., Rui, Y., Tang, X., ... & Zhu, S. (2016). Iron oxide nanoparticles as a potential iron fertilizer for peanut (Arachis hypogaea). Frontiers in plant science, 7, 815.

Sabir, S., Arshad, M., & Chaudhari, S. K. (2014). Zinc oxide nanoparticles for revolutionizing agriculture: synthesis and applications. *The Scientific World Journal*, *2014*.

Saha, A., Gupta, B. S., Patidar, S., & Martínez-Villegas, N. (2022). Spatial distribution based on optimal interpolation techniques and assessment of contamination risk for toxic metals in the surface soil. *Journal of South American Earth Sciences*, *115*, 103763.

Saifullah, Javed, H., Naeem, A., Rengel, Z., & Dahlawi, S. (2016). Timing of foliar Zn application plays a vital role in minimizing Cd accumulation in wheat. Environmental Science and Pollution Research, 23, 16432-16439.

Salam, A., Afridi, M. S., Javed, M. A., Saleem, A., Hafeez, A., Khan, A. R., ... & Gan, Y. (2022). Nano-priming against abiotic stress: A way forward towards sustainable agriculture. Sustainability, 14(22), 14880.

Salari, S., Bahabadi, S. E., Samzadeh-Kermani, A., & Yosefzaei, F. (2019). In-vitro evaluation of antioxidant and antibacterial potential of greensynthesized silver nanoparticles using Prosopis farcta fruit extract. Iranian journal of pharmaceutical research: IJPR, 18(1), 430.

Salavati-Niasari, M., Davar, F., & Mir, N. (2008). Synthesis and characterization of metallic copper nanoparticles via thermal decomposition. Polyhedron, 27(17), 3514-3518.

Salcido-Martinez, A., Sanchez, E., Licon-Trillo, L. P., Perez-Alvarez, S., Palacio-Marquez, A., Amaya-Olivas, N. I., & Preciado-Rangel, P. (2020). Impact of the foliar application of magnesium nanofertilizer on physiological and biochemical parameters and yield in green beans. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 48(4), 2167-2181.

Sanjivkumar, M., Vaishnavi, R., Neelakannan, M., Kannan, D., Silambarasan, T., & Immanuel, G. (2019). Investigation on characterization and biomedical properties of silver nanoparticles synthesized by an actinobacterium Streptomyces olivaceus (MSU3). Biocatalysis and agricultural biotechnology, 17, 151-159.

Santás-Miguel, V., Arias-Estévez, M., Rodríguez-Seijo, A., & Arenas-Lago, D. (2023). Use of metal nanoparticles in agriculture. A review on the effects on plant germination. Environmental Pollution, 122222.

Santhosh, P. B., Genova, J., & Chamati, H. (2022). Green synthesis of gold nanoparticles: An eco-friendly approach. Chemistry, 4(2), 345-369.

Saritha, G. N. G., Anjy, T., & Kumar, A. (2022). Nanotechnology - Big impact: How nanotechnology is changing the future of agriculture? *The Journal of Agriculture and Food Research*, *10*(12), 100457.

Scherer, M. D., Sposito, J. C. V., Falco, W. F., Grisolia, A. B., Andrade, L. H. C., Lima, S. M., Machado, G., Nascimento, V. A., Gonçalves, D. A., Wender, H., Oliveira, S. L., & Caires, A. R. L. (2019). Cytotoxic and genotoxic effects of silver nanoparticles on meristematic cells of *Allium cepa* roots: A close analysis of particle size dependence. *The Science of the total environment*, *660*, 459–467. https://doi.org/10.1016/j.scitotenv.2018.12.444.

Segatto, C., Souza, C. A., Fiori, M. A., Lajús, C. R., Silva, L. L., & Riella, H. G. (2023). Seed treatment with magnesium nanoparticles alters phenology and increases grain yield and mineral content in maize. Australian Journal of Crop Science, 17(2), 165-178.

Seregina, T., Chernikova, O., Mazhaysky, Y., & Ampleeva, L. (2021). The productivity of spring barley when using cobalt nanoparticles and liquid-phase biological product.

Shafey, A. M. E. (2020). Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review. Green Processing and Synthesis, 9(1), 304-339.

Sharma, P. (2023). Genotoxicity of the nanoparticles. In *The Impact of Nanoparticles on Agriculture and Soil* (pp. 115-128). Academic Press.

Sharma, P., Gautam, A., Kumar, V., & Guleria, P. (2022). In vitro exposed magnesium oxide nanoparticles enhanced the growth of legume Macrotyloma uniflorum. Environmental Science and Pollution Research, 1-11.

Sharmila, G., Thirumarimurugan, M., & Muthukumaran, C. (2019). Green synthesis of ZnO nanoparticles using Tecoma castanifolia leaf extract: characterization and evaluation of its antioxidant, bactericidal and anticancer activities. Microchemical Journal, 145, 578-587.

Shende, S., Rajput, V. D., Gade, A., Minkina, T., Fedorov, Y., Sushkova, S., ... & Boldyreva, V. (2021). Metal-based green synthesized nanoparticles: Boon for sustainable agriculture and food security. IEEE Transactions on NanoBioscience, 21(1), 44-54.

Sheykhbaglou, R., Sedghi, M., & Fathi-Achachlouie, B. (2018). The effect of ferrous nano-oxide particles on physiological traits and nutritional compounds of soybean (Glycine max L.) seed. Anais da Academia Brasileira de Ciências, 90, 485-494.

Shojaei TR, Salleh MAM, Tabatabaei M, Mobli H, Aghbashlo M, Rashid SA, Tan T (2019) Applications of nanotechnology and carbon nanoparticles in agriculture. Synthesis, technology and applications of Carbon Nanomaterials. Elsevier, pp 247–277

Shukla, K., Mishra, V., Singh, J., Varshney, V., Verma, R., & Srivastava, S. (2024). Nanotechnology in sustainable agriculture: A double-edged sword. *Journal of the science of food and agriculture*, 10.1002/jsfa.13342. Advance online publication. https://doi.org/10.1002/jsfa.13342

Siddiqi, K. S., & Husen, A. (2017). Plant response to engineered metal oxide nanoparticles. *Nanoscale Res Lett 12*: 92.

Siddiqi, K. S., ur Rahman, A., Tajuddin, N., & Husen, A. (2018). Properties of zinc oxide nanoparticles and their activity against microbes. Nanoscale research letters, 13, 1-13.

Siddiquee, S., Rovina, K., Yusof, N. A., Rodrigues, K. F., & Suryani, S. (2014). Nanoparticle-enhanced electrochemical biosensor with DNA immobilization and hybridization of Trichoderma harzianum gene. Sensing and Bio-Sensing Research, 2, 16-22.

Silva, S., Dias, M. C., & Silva, A. M. (2022). Titanium and zinc based nanomaterials in agriculture: A promising approach to deal with (a) biotic stresses?. Toxics, 10(4), 172.

Singh, A., Gautam, P. K., Verma, A., Singh, V., Shivapriya, P. M., Shivalkar, S., ... & Samanta, S. K. (2020). Green synthesis of metallic nanoparticles as effective alternatives to treat antibiotics resistant bacterial infections: A review. Biotechnology Reports, 25, e00427.

Singh, A., Singh, N. B., Hussain, I., Singh, H., & Singh, S. C. (2015). Plant-nanoparticle interaction: an approach to improve agricultural practices and plant productivity. Int. J. Pharm. Sci. Invent, 4(8), 25-40.

Singh, D., Kumar, A. (2020). Understanding the Effect of the Interaction of Nanoparticles with Roots on the Uptake in Plants. In: Dasgupta, N., Ranjan, S., Lichtfouse, E. (eds) Environmental Nanotechnology Volume 3. Environmental Chemistry for a Sustainable World, vol 27. Springer, Cham. https://doi.org/10.1007/978-3-030-26672-1_9

Singh, K. R., Nayak, V., Sarkar, T., & Singh, R. P. (2020). Cerium oxide nanoparticles: properties, biosynthesis and biomedical application. RSC advances, 10(45), 27194-27214.

Singh, M., Srivastava, M., Kumar, A., & Pandey, K. D. (2019). Biosynthesis of nanoparticles and applications in agriculture. In Role of plant growth promoting microorganisms in sustainable agriculture and nanotechnology (pp. 199-217).

Singh, R. P., Handa, R., & Manchanda, G. (2021). Nanoparticles in sustainable agriculture: An emerging opportunity. Journal of controlled release, 329, 1234-1248.

Singhal, R. K., Fahad, S., Kumar, P., Choyal, P., Javed, T., Jinger, D., ... & Nawaz, T. (2023). Beneficial elements: New Players in improving nutrient use efficiency and abiotic stress tolerance. Plant Growth Regulation, 100(2), 237-265.

Singla, R., Kumari, A., & Yadav, S. K. (2019). Impact of nanomaterials on plant physiology and functions. *Nanomaterials and plant potential*, 349-377.

Spanos, A., Athanasiou, K., Ioannou, A., Fotopoulos, V., & Krasia-Christoforou, T. (2021). Functionalized magnetic nanomaterials in agricultural applications. *Nanomaterials*, *11*(11), 3106.

StatNano, 2022. Nanotechnology Products Database (NPD) [WWW Document]. https://product.statnano.com/industry/agriculture (Accessed 11 May 2022)

Su, Y., Zhou, X., Meng, H., Xia, T., Liu, H., Rolshausen, P., ... & Jassby, D. (2022). Cost–benefit analysis of nanofertilizers and nanopesticides emphasizes the need to improve the efficiency of nanoformulations for widescale adoption. Nature food, 3(12), 1020-1030.

Subbaiah, L. V., Prasad, T. N. V. K. V., Krishna, T. G., Sudhakar, P., Reddy, B. R., & Pradeep, T. (2016). Novel effects of nanoparticulate delivery of zinc on growth, productivity, and zinc biofortification in maize (Zea mays L.). Journal of Agricultural and Food Chemistry, 64(19), 3778-3788.

Sukri, S. N. A. M., Shameli, K., Wong, M. M. T., Teow, S. Y., Chew, J., & Ismail, N. A. (2019). Cytotoxicity and antibacterial activities of plant-mediated synthesized zinc oxide (ZnO) nanoparticles using Punica granatum (pomegranate) fruit peels extract. Journal of Molecular Structure, 1189, 57-65.

Sultana, N., Raul, P. K., Goswami, D., Das, B., Gogoi, H. K., & Raju, P. S. (2018). Nanoweapon: control of mosquito breeding using carbon-dot-silver nanohybrid as a biolarvicide. Environmental chemistry letters, 16(3), 1017-1023.

Sun, Y., Zhu, G., Zhao, W., Jiang, Y., Wang, Q., Wang, Q., ... & Gao, L. (2022). Engineered nanomaterials for improving the nutritional quality of agricultural products: a review. *Nanomaterials*, *12*(23), 4219.

Sunderam, V., Thiyagarajan, D., Lawrence, A. V., Mohammed, S. S. S., & Selvaraj, A. (2019). In-vitro antimicrobial and anticancer properties of green synthesized gold nanoparticles using Anacardium occidentale leaves extract. Saudi journal of biological sciences, 26(3), 455-459.

Taheri, M., Qarache, H. A., Qarache, A. A., & Yoosefi, M. (2016). The effects of zinc-oxide nanoparticles on growth parameters of corn (SC704). STEM Fellowship Journal, 1(2), 17-20.

Tawfik, M. M., Mohamed, M. H., Sadak, M. S., & Thalooth, A. T. (2021). Iron oxide nanoparticles effect on growth, physiological traits and nutritional contents of Moringa oleifera grown in saline environment. Bulletin of the National Research Centre, 45, 1-9.

Tombuloglu, H., Slimani, Y., AlShammari, T. M., Tombuloglu, G., Almessiere, M. A., Sozeri, H., ... & Ercan, I. (2021). Delivery, fate and physiological effect of engineered cobalt ferrite nanoparticles in barley (Hordeum vulgare L.). Chemosphere, 265, 129138.

Tondey, M., Kalia, A., Singh, A., Dheri, G. S., Taggar, M. S., Nepovimova, E., ... & Kuca, K. (2021). Seed priming and coating by nano-scale zinc oxide particles improved vegetative growth, yield and quality of fodder maize (Zea mays). Agronomy, 11(4), 729.

Tortella, G., Rubilar, O., Pieretti, J. C., Fincheira, P., de Melo Santana, B., Fernández-Baldo, M. A., ... & Seabra, A. B. (2023). Nanoparticles as a promising strategy to mitigate biotic stress in agriculture. Antibiotics, 12(2), 338.

Tripathi, A., Liu, S., Singh, P. K., Kumar, N., Pandey, A. C., Tripathi, D. K., ... & Sahi, S. (2017). Differential phytotoxic responses of silver nitrate (AgNO3) and silver nanoparticle (AgNps) in Cucumis sativus L. *Plant Gene*, *11*, 255-264.

Tripathi, D., Singh, M., & Pandey-Rai, S. (2022). Crosstalk of nanoparticles and phytohormones regulate plant growth and metabolism under abiotic and biotic stress. Plant Stress, 6, 100107.

Ullah, A. M. A., Tamanna, A. N., Hossain, A., Akter, M., Kabir, M. F., Tareq, A. R. M., ... & Khan, M. N. I. (2019). In vitro cytotoxicity and antibiotic application of green route surface modified ferromagnetic TiO 2 nanoparticles. RSC advances, 9(23), 13254-13262.

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., ur Rehman, H., ... & Sanaullah, M. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. Science of the total environment, 721, 137778.

utility in pest management. Indian Farmer, 6: 17-21.

Valsalam, S., Agastian, P., Arasu, M. V., Al-Dhabi, N. A., Ghilan, A. K. M., Kaviyarasu, K., ... & Arokiyaraj, S. (2019). Rapid biosynthesis and characterization of silver nanoparticles from the leaf extract of Tropaeolum majus L. and its enhanced in-vitro antibacterial, antifungal, antioxidant and anticancer properties. Journal of Photochemistry and Photobiology B: Biology, 191, 65-74.

Vasantharaj, S., Sathiyavimal, S., Saravanan, M., Senthilkumar, P., Gnanasekaran, K., Shanmugavel, M., ... & Pugazhendhi, A. (2019). Synthesis of ecofriendly copper oxide nanoparticles for fabrication over textile fabrics: characterization of antibacterial activity and dye degradation potential. Journal of Photochemistry and Photobiology B: Biology, 191, 143-149.

Vasantharaj, S., Sathiyavimal, S., Senthilkumar, P., LewisOscar, F., & Pugazhendhi, A. (2019). Biosynthesis of iron oxide nanoparticles using leaf extract of Ruellia tuberosa: antimicrobial properties and their applications in photocatalytic degradation. Journal of Photochemistry and Photobiology B: Biology, 192, 74-82.

Venzhik, Y. V., Moshkov, I. E., & Dykman, L. A. (2021). Gold nanoparticles in plant physiology: principal effects and prospects of application. Russian Journal of Plant Physiology, 68(3), 401-412.

Verma, D. K., Patel, S., & Kushwah, K. S. (2021). Effects of nanoparticles on seed germination, growth, phytotoxicity and crop improvement. Agricultural Reviews, 42(1), 1-11.

Vigani, G., Zocchi, G., Bashir, K., Philippar, K., & Briat, J. F. (2013). Cellular iron homeostasis and metabolism in plant. Frontiers in plant science, 4, 490.

Vijayanandan, A. S., & Balakrishnan, R. M. (2018). Biosynthesis of cobalt oxide nanoparticles using endophytic fungus Aspergillus nidulans. Journal of environmental management, 218, 442-450.

Vinod Saharan, V. S., Garima Sharma, G. S., Meena Yadav, M. Y., Choudhary, M. K., Sharma, S. S., Ajay Pal, A. P., ... & Pratim Biswas, P. B. (2015). Synthesis and in vitro antifungal efficacy of Cu-chitosan nanoparticles against pathogenic fungi of tomato.

Waghmode, M. S., Gunjal, A. B., Mulla, J. A., Patil, N. N., & Nawani, N. N. (2019). Studies on the titanium dioxide nanoparticles: Biosynthesis, applications and remediation. SN Applied Sciences, 1(4), 310.

Wahid, I., Rani, P., Kumari, S., Ahmad, R., Hussain, S. J., Alamri, S., ... & Khan, M. I. R. (2022). Biosynthesized gold nanoparticles-maintained nitrogen metabolism, nitric oxide synthesis, ions balance, and stabilizes the defense systems to improve salt stress tolerance in wheat. Chemosphere, 287, 132142.

Wallace, R., Brown, A. P., Brydson, R., Wegner, K., & Milne, S. J. (2013). Synthesis of ZnO nanoparticles by flame spray pyrolysis and characterisation protocol. Journal of Materials Science, 48, 6393-6403.

Wu, F., Fang, Q., Yan, S., Pan, L., Tang, X., & Ye, W. (2020). Effects of zinc oxide nanoparticles on arsenic stress in rice (Oryza sativa L.): germination, early growth, and arsenic uptake. Environmental Science and Pollution Research, 27, 26974-26981.

Xun, H., Ma, X., Chen, J., Yang, Z., Liu, B., Gao, X., … & Pang, J. (2017). Zinc oxide nanoparticle exposure triggers different gene expression patterns in maize shoots and roots. *Environmental Pollution, 229,* 479-488.

Yadav, A., Yadav, K., Ahmad, R., & Abd-Elsalam, K. A. (2023). Emerging frontiers in nanotechnology for precision agriculture: Advancements, hurdles and prospects. Agrochemicals, 2(2), 220-256.

Yadav, R., Saini, H., Kumar, D., Pasi, S., & Agrawal, V. (2019). Bioengineering of Piper longum L. extract mediated silver nanoparticles and their potential biomedical applications. Materials Science and Engineering: C, 104, 109984.

Yan, D., Duermeyer, L., Leoveanu, C., & Nambara, E. (2014). The functions of the endosperm during seed germination. Plant and Cell Physiology, 55(9), 1521-1533.

Yang, G., Yuan, H., Ji, H., Liu, H., Zhang, Y., Wang, G., ... & Guo, Z. (2021). Effect of ZnO nanoparticles on the productivity, Zn biofortification, and nutritional quality of rice in a life cycle study. Plant Physiology and Biochemistry, 163, 87-94.

Yasmeen, F., Raja, N. I., Ilyas, N., & Komatsu, S. (2018). Quantitative proteomic analysis of shoot in stress tolerant wheat varieties on copper nanoparticle exposure. Plant molecular biology reporter, 36, 326-340.

Yih, T. C., & Al-Fandi, M. (2006). Engineered nanoparticles as precise drug delivery systems. *Journal of cellular biochemistry*, *97*(6), 1184-1190.

Yin, L., Colman, B. P., McGill, B. M., Wright, J. P., & Bernhardt, E. S. (2012). Effects of silver nanoparticle exposure on germination and early growth of eleven wetland plants.

Yoo-Iam, M., Chaichana, R., & Satapanajaru, T. (2014). Toxicity, bioaccumulation and biomagnification of silver nanoparticles in green algae (Chlorella sp.), water flea (Moina macrocopa), blood worm (Chironomus spp.) and silver barb (Barbonymus gonionotus). *Chemical Speciation & Bioavailability*, *26*(4), 257-265.

Yuan, J., Chen, Y., Li, H., Lu, J., Zhao, H., Liu, M., ... & Glushchenko, N. N. (2018). New insights into the cellular responses to iron nanoparticles in Capsicum annuum. *Scientific reports*, *8*(1), 1-9.

Yüksel, S., Schwenkbier, L., Pollok, S., Weber, K., Cialla-May, D., & Popp, J. (2015). Label-free detection of Phytophthora ramorum using surface-enhanced Raman spectroscopy. Analyst, 140(21), 7254-7262.

Zaheer, T., Ali, M. M., Abbas, R. Z., Atta, K., Amjad, I., Suleman, A., ... & Aqib, A. I. (2022). Insights into nanopesticides for ticks: the superbugs of livestock. Oxidative medicine and cellular longevity, 2022.

Zhang, D., Ma, X. L., Gu, Y., Huang, H., & Zhang, G. W. (2020). Green synthesis of metallic nanoparticles and their potential applications to treat cancer. Frontiers in chemistry, 8.

Zhang, H., Zhao, X., Bai, J., Tang, M., Du, W., Lv, Z., ... & Mao, H. (2024). Effect of ZnO nanoparticle application on crop safety and soil environment: a case study of potato planting. Environmental Science: Nano, 11(1), 351-362.

Zhang, X. F., Liu, Z. G., Shen, W., & Gurunathan, S. (2016). Silver nanoparticles: synthesis, characterization, properties, applications, and therapeutic approaches. International journal of molecular sciences, 17(9), 1534.

Zhao, W., Ma, T., Zhou, P., Wu, Z., Tan, Z., & Rui, Y. (2024). Insights into the effect of manganese-based nanomaterials on the distribution trait and nutrition of radish (Raphanus sativus L.). Plant Physiology and Biochemistry, 108428.

Zhao, Y., Liu, L., Kong, D., Kuang, H., Wang, L., & Xu, C. (2014). Dual amplified electrochemical immunosensor for highly sensitive detection of Pantoea stewartii sbusp. stewartii. ACS Applied Materials & Interfaces, 6(23), 21178-21183.

Zheng, L., Hong, F., Lu, S., & Liu, C. (2005). Effect of nano-TiO 2 on strength of naturally aged seeds and growth of spinach. Biological trace element research, 104, 83-91.

Zhou, P., Jiang, Y., Adeel, M., Shakoor, N., Zhao, W., Liu, Y., ... & Zhang, P. (2023). Nickel oxide nanoparticles improve soybean yield and enhance nitrogen assimilation. Environmental Science & Technology, 57(19), 7547-7558.

Zhu, J.; Li, J.; Shen, Y.; Liu, S.; Zeng, N.; Zhan, X.; White, J.C.; Gardea-Torresdey, J.; Xing, B. Mechanism of zinc oxide nanoparticle entry into wheat seedling leaves. Environ. Sci. Nano 2020, 7, 3901–3913.

Zulfiqar, F., & Ashraf, M. (2021). Nanoparticles potentially mediate salt stress tolerance in plants. Plant Physiology and Biochemistry, 160, 257-268

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A., & Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: Advantages and limitations. Plant Science, 289, 110270.