DOI: https://doi.org/10.70749/ijbr.v3i8.1867

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://induspublishers.com/IJBR
ISSN: 2960-2793/ 2960-2807

Advances in Plant-Based Nanoparticles: From Biosynthesis to Abiotic Stress Resilience in Crops

Aqsa Javaid[1], Khunsa Saeed[1], Javed Kamar[2], Muhammad Tahir[3], Sohail Kumar[4], Usman Ahmed[5], Zainab[6], Maryam Jameela[7], Muhammad Asadullah Usman[8], Sajid Hussain[2]

[1]SA-CIRBS, International Islamic University, Islamabad, Pakistan.
[2]Department of Botany, PMAS-Arid Agriculture University, Rawalpindi, Punjab, Pakistan.
[3]Department of Biological Sciences, Govt. Jinnah Islamia Graduate College, Sialkot, Punjab, Pakistan.
[4]Department of Zoology, Govt. Murray Graduate College, Sialkot, Punjab, Pakistan.
[5]Department of Physical Education, Govt. Jinnah Islamia Graduate College, Sialkot, Punjab, Pakistan.
[6]Department Biological Sciences, University of Sialkot, Sialkot, Punjab, Pakistan.
[7]University Institute of Biochemistry and Biotechnology, PMAS Arid Agriculture University, Rawalpindi, Punjab, Pakistan.
[8]Beaconhouse, Newlands Islamabad, Pakistan.

ARTICLE INFO

Keywords: Abiotic Stressors, Characterization of Nanoparticles, Eco-Friendly, Nano Fertilizers.

Correspondence to: Khunsa Saeed, SA-CIRBS, International Islamic University, Islamabad, Pakistan.
Email: khunsa.phdns26@iiu.edu.pk &
Sajid Hussain,
Department of Botany, PMAS-Arid Agriculture University, Rawalpindi, Punjab, Pakistan.
Email: sajidhussaindgk121@gmail.com

Declaration
Authors' Contribution
All authors equally contributed to the study and approved the final manuscript

Conflict of Interest: No conflict of interest.

Funding: No funding received by the authors.

Article History
Received: 23-04-2025 Revised: 16-07-2025
Accepted: 29-07-2025 Published: 01-08-2025

ABSTRACT

Abiotic stress is the unfavorable impact of nonliving materials on living organisms in a particular environment. Major global challenges include possible pressures i.e. salinity, drought, high or low temperatures, heavy metals and other ecological limits. Plants are more prone to abiotic stress as the climate changes globally. The plants react to these challenges by activating several complex systems that modify the biochemical and morpho-physiological courses in them. Therefore, to create sustainable agricultural systems for crop production, technological progress of nanoparticles (NPs) necessitates the development to combat the harmful impacts of abiotic environmental restrictions. The various NPs used to treat plants to overcome environmental challenges include TiO2, Zn, ZnO, Ce, Co, Cu, Se, Ag, Si, Au, SiO2, FeO, Fe2O3, CaCO3, Mg, MgO, Mn, etc. These promise to boost crop productivity by enhancing abiotic stress tolerance mechanisms in crops. Enhancement of root growth, aquaporins activation, altered intra-cellular water metabolism, ionic equilibrium and accumulation of solutes were the primary processes through which NPs reduced osmotic stress due to water scarcity. As nano-fertilizers, NPs have attracted considerable interest hiving elevated ratio of surface area to volume, eco-friendliness, inexpensive, distinctive physicochemical characteristics and enhanced plant production. Numerous investigations had specified the prospective function of NPs in the control of abiotic stress. This review highlighted green synthesis, characterization of NPs and their function in mitigating abiotic stresses and promoting development to build a lucrative and environment-friendly approach to future sustainability of agriculture.

INTRODUCTION

Nanotechnology is a science of maneuvering matter at nanoscale, including their design, manufacture, characterization, using structures, devices and systems via altering of particle size and shape at nanoscale. In contemporary period, it is evolving as the revolutionary tool Rudra & Kingsley 2025). It is regarded as a developing branch of research that is extensively subjugated in many scientific fields and is expected to take a leading position in food science and agriculture in the subsequent century, but there is lack of scientific studies regarding their appliance in agriculture. Plant nourishment is essential for agricultural production, crop quality, for which application of fertilizers accounts for 40-65% of global food production (Abobatta, 2018).

Nanoparticles encompass a big surface area and a tiny size of 1–100 nm, bearing multiple potential applications. These have emerged as potentially useful agents for plant growth, insecticides and fertilizers. Insects, fungi and weeds are among the plant pests that nanoparticles have been investigated as an alternate control method in recent years (Karthik et al., 2025). In addition to their antibacterial capabilities, numerous nanoparticles (Fe, Ag, Si, Al, Cu, Zn, TiO_2, CeO_2, ZnO, Al_2O_3 and carbon nanotubes) showed negative impacts on plant growth. In food industry, nanoparticles bear a significant part in producing foods with superior quality and nutritious value (Ghidan and Antary, 2019).

Nanoparticles have gained significance in the fields of medicine, technology, agricultural domains, *etc* and possess distinct physicochemical features. These are created by decomposing bigger molecules by electro-explosion, laser ablation, sputtering, chemical methods of etching, mechanical milling and manufacture of metal-oxide nanoparticles through spinning, sol-gel process, condensation, pyrolysis, *etc* (Ray et al., 2025). Important to success of nanoparticle synthesis are following characterizations: microscopic characterizations of morphology (scanning and transmission electron microscopy). Characterizations of the nanoparticles is done through XRD, Raman and Zeta-size analyzers, XPS, photoluminescence and UV-visible. In case of green synthesis, processed plants extracts, fungi or microbes react solutions with metal salt, consequence in generation of metal NPs encrusted with the desired biomolecules. Owing to their small size, green-synthesized NPs serve in effectual conveying to the target position and contribute to improved outcomes (Al- Khayri *et al*., 2023).

Potential applications of NPs for enhancing plant resistance to abiotic stress include; calcium oxide, copper, zinc oxide, silica, iron nanoparticles used against heavy metal abiotic stress, iron oxide, zinc oxide, silica, maghemite, selenium nanoparticles used against drought stress in plants, titanium nanoparticles in the heat stress management, silver and titanium oxide against cold stress and cerium oxide, titanium oxide, chitosan, silver, zinc, silicon, gold and cerium dioxide nanoparticles used against the salinity stress in the plants (Manzoor *et al*., 2022).

For outstanding reactivity, distinctive physic-chemical traits and amazing cellular durability of NPs have achieved substantial significance in molecular biology. However, these may affect the plant system both positively and negatively. Several nanoparticles can induce oxidative damage to biomolecules at extremely high concentrations, resulting in plant cell damage and level cell death. However, at ideal levels of small nanomolar-concentrations, NPs serve as essential plant maturity and growth regulators (Nejatzadeh, 2021).

Advantages and Disadvantages of Using Nanoparticles in Plants

More than 60% of the population in the majority of developing nations depends on agriculture for their livelihood. Concurrently, the agriculture industry faces numerous issues, including climate change, excessive use of resources, and excessive application of chemical fertilizers. Direct applications of nanotechnology in agriculture embrace the deliverance of agrochemicals, nutrients, nanoscale transporters, veterinary care, insecticides, intelligent packaging, nano sensors, fisheries, aquaculture and identification of the nutrient insufficiency (Abobatta, 2018). Owing to the distinctive properties, NPs enabled our farmers to resolve numerous agricultural issues. This technology is capable of enhancing the soil's quality with nutrients that promote increased yield, facilitating the process to make certain whether plants have access to their requisite nutrients, influencing the improvement of genetic features of plants, the delivery of genes, DNA molecules, and medication molecules to a specific spot in plants to generate insect-repellent properties (Atanda et al., 2025). The tools based on nanotechnology, such as quantum dots, are employed correctly for the daily monitoring of infections. Nanoencapsulation decreases the leaching and evaporation of dangerous substances, so contributing significantly to environmental protection (Siddiqui *et al*., 2015).

Nanotechnology employs various chemical agents, unique delivery mechanisms to increase crop yield and potential to reduce the usage of bulk agrochemicals and provided sharper solutions to agriculture's existing constraints. Nano-fertilizers are being employed as alternatives to bulk fertilizers and to decrease soil and water contamination by various agrochemicals (Arora et al., 2024). Nano fertilizers promote the deliberate and consistent discharge of nutrients, hence reducing nutrient loss and increasing nutrient usage efficiency. Slow-release fertilizers are a good substitute for soluble fertilizers, as nanotechnology enhances nutrient use efficiency and minimizes the expense of environmental protection ((Abobatta, 2018). Figure 1 that was adopted from

Nanoparticles had aided in enhancing stress tolerance and plant growth. Utilizing biosynthesized nanoparticles, nano-agriculture confers several benefits to plants via reduced influence of biotic and abiotic environmental challenges. These pressures have deleterious impacts on plants by changing their yield capacity and homeostatic balance (Rehmanullah *et al*., 2020). Biosynthesis of nanoparticles has unique impacts on plants, including an improvement in antioxidant status and a reduction in produced reactive oxygen species that affect multiple biochemical and molecular cell signaling trails, enhancing crop yield. These stimulate plant growth by promoting growth of roots, shoots, biomass yield and seed germination (Khan *et al*., 2022). These materials are utilized in plant development and crop production, including nano-pesticides, nano-fertilizers, nanobiotechnology and nano sensors. Distinctive features of NPs included large surface area, concentrated size distribution, and great biocompatibility, enhance the efficacy and durability of agrochemicals. In addition, the use of suitable nanomaterials during plant growth phases or stress circumstances promotes plant growth and increases its stress resistance. In addition, developing nanotools and nanobiotechnology gave a new platform for molecular crop monitoring and modification (Liu *et al*., 2021).

The appliance of NP-based fertilizers accelerates germination, augments plant resistance to biotic and abiotic stressors and boosts their development while decreasing environmental impact. The disproportionate utilization of chemical fertilizers for increasing crop productivity reduces soil fertility, contaminates land and water, and poses dangers to human health. To address the problem of ever-increasing food demand, a significant increase in fertilizer use is anticipated. Nanotechnology breakthroughs offer significant benefits for reducing chemical fertilizers usage bearing ill effects on the ecosystem and human health (Tarkeshwar *et al*., 2022).

Despite numerous roles and applications in plants, the nanoparticles also bear unpleasant effects on plants and animals additionally. For having tendency of easy penetration in cells, in humans and animals, commonly utilized nanoparticles (Zn, Ag, TiO2, Au, ZnO, MgO, and

SiO_2) pose numerous health hazards (Khan *et al*., 2022). NPs enter cells and interrupt Electron transport system in chloroplasts and mitochondria, causing an oxidative disintegration with elevated ROS contents. Cells when exposed to excessive quantities of ROS, their DNA degradation, protein oxidation, lipid peroxidation and membrane damage occur, ultimately leading to cell death. Therefore, metal-based nanoparticles can produce oxidative stress in numerous plant species. ROS causes oxidative damage of chloroplast and mitochondrial DNA, resulting in dysfunction and complete inactivation (Goswami *et al*., 2019).

Biomagnifications, biotransformation and bioaccumulation of designed NPs in food crops are currently poorly known. A few NPs and plant species have been examined in terms of nanoparticle accumulation and consequent availability in the crops (Dey et al.,2025). These NP also attach to plant roots and impose physical or chemical harm to plants. A study investigated the phytotoxicity of five different types of NPs (aluminum, zinc, multi-walled carbon nanotube, zinc oxide, alumina) and it was found that some of the NPs badly affected the root growth. Even at low exposure to this, plant growth and soybean pod size were diminished (Agrawal and Rathore, 2014). Recuperation of plant output is influenced by fertilizer type, fertilization method, dimensions and dose, therefore, using nanotechnology in agriculture without proper understanding and certain examinations could bring unpleasant impacts on human health and ecosystem (Mohammed, 2021).

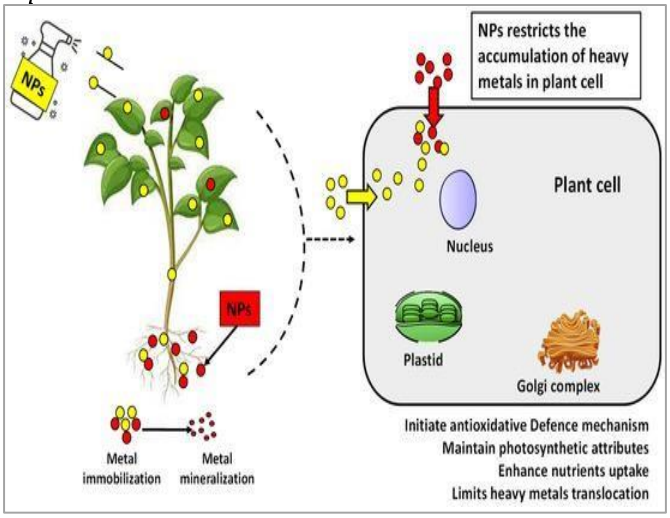
Abiotic Stress Factors and their Impact on the Plants Physiology

Climate change is a global concern that directly or indirectly reduces the biosphere's production and productivity due to abiotic and biotic stress. Hans Selye introduced the notion of stress in 1936 as negative environmental limits for plants (Selye H., 1936). Stress is the factor that limits an individual's genetic capacity for growth, development, and reproduction by inhibiting normal function. In the context of agriculture, stress is the factor that affects crop yield and destroys biomass. Based on the involvement of stress-causing factors, stress can be broadly classified as biotic stress, which is the result of interactions between organisms for resources, predation, and allelopathic effects, and abiotic stress, which is the result of interactions between organisms and their physical environment. Abiotic conditions limit crop selection, whereas large-scale production and extreme events result in crop failure (Rawat and Tripathi, 2020).

Abiotic stress is the unfavorable impact of nonliving materials on living organisms in a particular environment. Major global challenges include possible pressures such as salt, drought, extremely low down or elevated temperatures, other ecological limits and heavy metals, Plants are more subject to abiotic stress as the climate changes globally. Climate transformation is connected with the hasty increase in frequency and severity of heat waves, droughts and additional abiotic stress events, *i.e.* salinity, flooding and freezing temperatures (Al- Khayri *et al*., 2023). To increase plant resistance against abiotic stress, numerous promising strategies are being researched. These include the application of NPs, which have been found to improve plant function under stressful situations. By absorbing the signals of trace elements in the soil, NPs can be implied to nourish the plants, cope plant diseases, combat pathogens and detect the presence of trace elements. A greater knowledge of the mechanisms through which nanoparticles aid plants in coping with abiotic challenges would aid in the creation of more enduring strategies to combat such stresses (Khalid *et al*., 2022). The figure 1 was illustrate by Khalid et al., (2022), the how nanoparticles help to cope with the abiotic stress in plants.

Figure1

Illustration of nanoparticle coping against the abiotic stress in plants.



Abiotic stressors include severe temperature, drought, flooding, salt and heavy metals, significantly impact plant growth, development and production. These unfavorable environmental circumstances impair the performance of crop plants by 50 to 70 percent, resulting in a yield reduction (Kumat at el., 2025). It is considered that emission of greenhouse gases from many sources, is one of the causes of progressive rise in world average temperature (global warming). In addition to altering precipitation patterns, global warming has contributed to irregular drought and flood. While in vegetative and reproductive stages of plant proliferation, abiotic stimuli, notably drought and heat hassle, is detrimental to biomass, grain acquiesce and product quality. A combination of abiotic factors had a significantly ill impact on crop yield and quality (Iljkić et al.,2025). Nevertheless, plant responses to these stimuli might vary by species and developmental stage. Water deficiency (drought) and increased warmth elicit stress-associated metabolic responses, and stomatal closure greatly reduces CO_2 uptake. Consequently, reduction equivalents (e.g. NADPH + H^+) required for CO_2 fixation via the Calvin cycle (i.e., CO_2 fixation) decrease significantly. Not only the photosynthetic process but also the biosynthetic processes involved in proteins, lipids, and minerals metabolism are affected by adaptive reactions. The abiotic stressors bear substantial impact on the protein, carbohydrate, mineral and lipid compositions owing to their metabolic changes (Kumar, 2020).

In the presence of drought stress, an increase in soil temperature becomes significantly more severe. Under field conditions, water deficit (drought) stress and high air temperature sometimes occur simultaneously, rendering a global challenge to agriculture to sustain food production. Under abiotic stress, plants experience a deficiency of vital components and an imbalance of nutrients, resulting in a decline in yield and quality (Zhan et al., 20250). Stressors too influence buildup of metabolites in the plant's edible sections, occasionally favorable through concentrating nutraceutical and stress-related metabolites, valued in human nutrition as health-related substances. Recently, salt stress is recommended as a prospective stressor for expanding fruits and vegetables quality (Rouphael *et al.*, 2018; Toscano *et al.*, 2019).

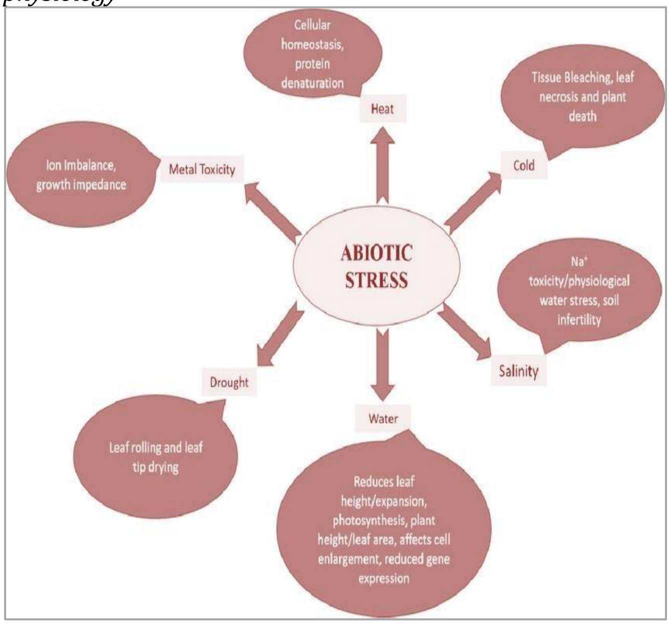
Vegetable crops bear diverse physiological, biochemical, metabolic, and morphological reactions to stressful situations, which can result in alterations in the chemical composition and visual appearance of ultimate yield. Salinity is regarded as a chemical eustressor since it was demonstrated to influence equally physical quality and chemical composition of a variety of vegetable commodities (Rouphael *et al.*, 2018). Salinity can be found in arid, semi-arid and coastal regions, where proximity to the sea has a significant impact on soil and water quality. Furthermore, in case of soilless cultivations concluding hydroponically grown leafy greens, poor water quality or suboptimal management of fertilizer solutions can create a stressful environment for the plants. Due to salt, plants must contend with a drop in the soil's water potential and a nutritional imbalance, which ultimately leads to a decrease in production and a decline in quality. The buildup of antioxidant chemicals, osmotically active metabolites and particular secondary metabolites are a few of the mechanisms established by plants to resist the increase in salt content (Parvaiz and Satyawati, 2008).

Another climatic condition that limited growing seasons of diverse plant species is the cold. Cold stress is classified into freezing and chilling strains. Its influence on plants depends upon its severity and duration. Seedling stage of plant is most susceptible to cold conditions. Common signs include the formation of a lesion on surface, discoloration, decreased shelf life, induced senescence, ethylene production and desiccation. Besides dramatic phenotypic alterations, chilling induces major biochemical and physiological changes, which were extensively reviewed (Acharya et al., 2025). Briefly, these alterations bear increase in cellular Ca^{+} levels, accumulated ROS, decreased fluidity in membrane pertaining to un-saturated fatty acids of membranes and compositional alterations in lipids to proteins ratios of the membranes. Low temperatures also result in dehydration, chiefly due to inability of absorbing ample water. Similarly, freezing can harm membranes owing to extreme dryness and the development of ice. The production of ice in intracellular regions can disturb cells and tissues physically. Freezing can result in denatured proteins and the precipitation of solutes. Freezing and chilling, like other abiotic stressors, cause the generation of ROS, thus disrupting the cellular redox state (Imran *et al.*, 2021).

Heavy metals (HM) including Cd, Mn, Co, Zn, Cu, Hg, Fe,Ni, etc have built up in soils due to anthropogenic activities including application of fertilizer, inappropriate industrial wastes disposal, unregulated sewage disposals and pococurante disposal of automotive effluents. These either leach into groundwater or deposited on soil surface. A serious component of HM stress is being non-biodegradable. Enzymes are inactivated or denatured due to the harmful effects of HM stress. These impede with substitution and interaction of critical metallic ions to biomolecules, disrupting membrane's integrity and posing alterations in photosynthetic capacity, respiration, etc. HMs too stimulate the generation of hydrogen peroxide, superoxide radicals and hydroxyl radicals. Addition of HMs, predominantly in roots due by blocking their Casparian strips or confined to root cell walls, hinder physio-morphological activities of plants, hence reducing crop yield (Shahid *et al.*, 2015).

Figure 2

Types of abiotic stressors influencing the plants and their physiology



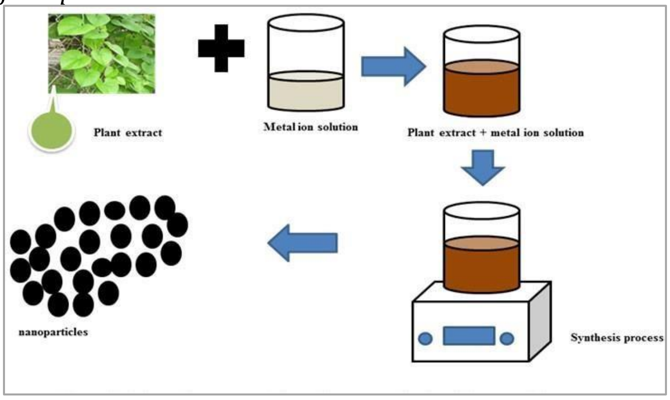
Plant-based Nanoparticles Production

Nanotechnology is a rapidly emerging, multidisciplinary field with several scientific and technological applications incorporating the sciences of engineering, chemistry, biology and physics, to develop unique techniques for regulating and creating nanoparticles. There is an urgent need to create NPs production technologies that are non-toxic and environmentally benign. Several safe, reproducible, simple, cost-effective, scalable green synthesis methods for nanoparticles were developed in current years, inspired by code of safety by design. Consequently, numerous biological systems, including bacteria, fungus, plant extracts and yeast are widely exploited in green synthesis techniques for production of NPs. The plant-based NP green synthesis is presently recognized as the gold standard, amid these green biological approaches for its usability and plant variety (Hano and Abbasi, 2022).

This review serves as a quick summary of existing advances in green synthesis, characterization, and employing of various plant-derived NPs in crops (Figure 2).

Figure 3

General schematic illustration on green synthesis of NPs from plant extracts



Green Synthesis of NPs from Roots of the Plants

The metal nanoparticles production by environmentally friendly synthetic trails employing plant extracts attracted more interest for its inexpensive, benevolent processes, smaller quantity of harmful byproducts and uses (Table 1). Under ambient conditions, AgNPs were produced by treating root extracts (aqueous) of *Rubus ellipticus Sm*. in 1 mM $AgNO_3$ solution (Khanal *et al*., 2022). Biosynthesis of silver and gold NPs from Zingiber officinale root extracts is governed by reducing power of endogenous phenylpropanoids, shagaols, oxalic acid, paradol, gingerol, zingerone and ascorbic acid. In addition, presence of different bioactive metabolites, including sitoindosides, flavonoids and amino acids yielded titanium oxide nanoparticles generated from *Withania somnifera* roots. X-ray diffraction analysis, on the other hand, deciphered hexagonal lattice structure of silver NPs derivative from root extracts of the *Rheum turkestanicum*, via reduction of Ag+ to Ag0, for the high levels of endogenous anthraquinone and phenolic compounds in *Rheum turkestanicum* roots (Chakraborty *et al*., 2022). The ethanolic root extracts of *Aconitum toxicum reichenb*, reduced by $HAuCl_4$ for 03 hours at room temperature were implied to manufacture AuNPs. Total extracts' polyphenol content were tested at 1.49 percent, while aconitine levels were determined at 4.89 mg/ml (Bao *et al*., 2021).

Green Synthesis of the NPs from the Stems of Plants

Stem methanolic extract of *Callicarpa maingayi* was employed in manufacture of silver nanoparticles, resulting in synthesis of Ag(Callicarpa maingayi)+complex. The extracts' aldehyde groups were primarily responsible for alteration of Ag ions into metallic AgNPs. The discrete functional group AC0, CN denotes amide I, the polypeptides responsible for the encapsulation of ionic chemicals into metallic NPs. The silver nanoparticles photosynthesis via Cissus quadrangularis extracts was also described. Silver ions were reduced by different functional groups, including amine, phenolic and carboxyl chemicals, which were visible in plant stems extract (Kuppusamy *et al*., 2016). The stem extracts of *Momordica charantia*, *Coleus aromaticus* and *Salvadora persica* were used to produce silver nanoparticles. The *Leucas lavandulifolia* stem extracts were used to produce selenium nanoparticles with a spherical shape. In addition, zinc oxide nanoparticles were biosynthesized from *Swertia chirayita* stem extracts displayed increased photocatalytic, structural, and significant antibacterial action (Saha *et al*., 2021).

Green Synthesis of NPs from Leaves of Plants

Silver nanoparticles were produced by boiling 10g of *Nelumbo lucifera* leaves in 100ml distilled water. This filtrate (12 ml) was then treated with 1 mM aqueous $AgNO_3$ solution (88 ml) and incubated (at room temperature) in dark. The silver nanoparticles (AgNPs) were synthesized, characterized through brownish-yellow hue solution. *Hibiscus rosa sinensis* leaf extracts were supplemented to 103M $AgNO_3$ solution and hence brownish-light silver nanoparticles were yielded. Salix alba leaf extracts were used in manufacturing the gold NPs. These were also recently synthesized by a variety of plant extracts, including *Bacillus marisfavi*, *Cofea Arabica*, *Croton sparsiforus, Citrus lim* and *Croton Caudatus Geisel* eaf extracts. Leaf extracts from *Camellia sinensis* (Black tea) were also utilized as reducing and stabilizing agent in manufacturing the PdNPs (Jadoun *et al*., 2021). The synthesis of platinum nanoparticles from *Diospyros kaki* leaf extracts was accomplished via maintaining reaction temperature of 95C and utilizing a leaf broth concentration of 10% or higher (Chakraborty *et al*., 2022). The copper-silver bimetallic NPs were biosynthesized from *Vitex negundo* leaves extracts having vital uses in packaging material for food (Mamatha *et al*., 2021).

Green Synthesis of NPs from the Flowers

Diverse chemicals included in diverse floral extracts function as oxidizing or reducing agents or as biotemplates to serve in green creation of nanoparticles, notably metal or metal oxide NPs. Silver NPs were synthesized from flower extracts of *Catharanthus roseus, Caesalpinia pulcherrima, Plumeria rubra, Lablab purpureus and Tagetes erecta*, gold nanoparticles from Tussilago farfara, Mangifera indica, Plumeria alba Linn and Gnidia glauca. Other NPs including copper, iron, zinc, cadmium, titanium and magnesium were synthesized from the flower extracts of *Mimusops elengi, Piliostigma thonningii, Nyctanthes arbor-tristis, Jacaranda mimosifolia, Calotropis gigantean* and *Rosmarinus officinalis L*, respectively (Kumar *et al*., 2020). Buds of *Syzygium aromaticum* have been utilized extensively in biosynthesis of variety of NPs, including copper, silver, palladium, copper oxide and gold NPs. Similar phytoagents, such as phenolics and flavonoids were found in the *Couropita guianensis* bud extracts, which inuced the silver NPs production. *Tussilago farfara* bud extracts containing sesquiterpene reducing agents facilitated the production of spherical Au and Ag NPs (Chakraborty *et al*., 2022).

Green Synthesis of the NPs from Plants' Seeds

For the formation of nanoparticles in a sustainable manner, seeds offer a low-cost, eco-friendly, non-toxic, and energy-free method. Using seed extracts, seed exudates, endosperms of *Coffea italica* and *Sinapis arvensis*, silver nanoparticles have been efficiently generated. Zinc oxide and Fe_3O_4 nanoparticles produced from seed extracts (*Punica granatum* and *Peganum harmala* seeds) exhibit significant chromium absorption and photocatalytic activity, respectively (Chakraborty *et al*., 2022). Silver nitrate NPs were derived from seed extracts of various Brassicaceae family crop seeds. All nanocomposites were completely characterized in the solid state using diversified techniques, including atomic force microscopy, UV–vis spectrophotometer and XRD (Singh *et al.*, 2018).

Table 1
Production of plant-based nanoparticles and their morphology

S. No	Plant source of nanoparticles	Name of nanoparticles	Size and shape of nanoparticles	Reference
1	Lolium multiform Aloe vera Vigna radiata Zea mays Allium sativum Baccopa monnieri Anacardium occidentale Citrus sinensis Eclipta prostrate Sorghum bicolor Triticum aestivum	Silver (Ag)	20-50 nm Spherical and cuboidal	Goswami *et al.*, 2019 Vannini *et al.*, 2013
2	Aloe vera Terminalia catappa Vitex negundo Anacardium occidentale Azadirachta indica Chenopodium album Mangifera indica	Gold (Au)	1-100nm Spherical and short ferret	Goswami *et al.*, 2019
3	Lycopersicum esculentum *Cassia fistula* *Melia azadarach* *Cayratia pedata*	Zinc (Zn)	30-100nm Rectangular	Naseer *et al.*, 2020
4	Camellia sinensis Hordeum vulgare Rumex acetosa Passiflora tripartitavar Terminalia chebula	Iron (Fe)	4.8-10nm Spherical, cuboidal or hexagonal	Saif *et al.*, 2016
5	*Coriandrum sativum* *Hagenia abyssinica* *Punica granatum* *Citrus medica Linn* *Zingiber officinale* *Ginkgo biloba Linn* *Plantago asiatica* *Thymus vulgaris*	Copper (Cu)	40-55nm Cuboidal, rods, or tetrahedral	Abbas *et al.*, 2020 Murthy *et al.*, 2020
6	Musa paradisica Gardenia jasminoides Anogeissus latifolia Ocimun sanctum Pulicaria glutinosa Curcuma longa Doipyros kaki Cinnamom zeylanicum Glycine max Pinus resinosa Cinnamomum camphora	Paladium (Pd)	200-250nm Cuboidal, dodecahedral or octahedral	Siddiqi *et al.*, 2016
7	*Lonicera japonica* *Syzygium cumini* *Cedrus deodar* *Eleaocarpus sphaericus* *Bauhinia variegate*	Poly lactic acid (PLA)	180-200nm Curved surfaces on the crystalline structure	Kumari *et al.*, 2012 Yu et al., 2025
8	Aloe vera Citrus aurantifolia Parthenium hysterophorus Physalis alkekengi Hibiscus subdariffa	Zinc oxide (ZnO)	30-200nm Rectangular	Goswami *et al.*, 2019
9	*Cucumis prophetarum* *Phyllanthus emblica* *Acidovorax oryzae*	Silver nitrate ($AgNO_3$)	20-42nm Spherical or cuboidal	Abbas *et al.*, 2020
10	Psidium guajava Glycosmis cochinchinensis Moringa oleifera Aloe barbadensis Miller Jatropha curcas	Titanium oxide (Ti_2O_3)	20-300nm Spherical or rods	Sethy *et al.*, 2020
11	*Azadirachta indica* *Nigella sativa* *Terminalia chebula* *Osimum sanctum* *Punica granatum*	Platinum (Pt)	2-100nm Irregular prismatic, cubic, icosahedral or tetrahedral	Fahmy *et al.*, 2020

12	Osimum sanctum Citrus limon Avena sativa Brassica juncea Coriandrum sativum	Lutetium oxide (Lu_2O_3)	15-100nm Spherical	Singh *et al*., 2018
13	*Hibiscus rosa sinensis* *Hibiscus cannabinus*	Ferric oxide (Fe_3O_4)	8-12nm Spherical	Buarki *et al*., 2022
14	Kalopanax pictus *Kappaphycus alvarezii* *Gardenia resinifera*	Manganese dioxide (MnO_2)	25-30nm Nanorods, elongated or square shaped	Moon *et al*., 2015
15	Punica granatum Vigna radiata Bryophyllum pinnatum	Silicon dioxide (SiO_2)	5-450nm Amorphous and spherical	Jadhao *et al*., 2020
16	Solanum lycopersicum Aurundianria pigmaea Satureja hortensis Triticum aestivum	Silicon (Si)	20-200nm Amorphous and spherical	Moscoso *et al*., 2022

Potential of NPS to Cope Abiotic Stress in Crops

Different abiotic pressures caused by climate change had substantial influence on plant growth and output. Frequent abiotic stresses are temperature extremes, drought, nutritional imbalances, heavy metals and salinity, contributing to major crop yield losses in many parts of the world, ultimately contributing to food insecurity. To increase plant resistance to abiotic stress, numerous promising strategies are being researched. These include the application of nanoparticles, which have been found to improve plant function under stressful situations. By absorbing the signals of trace elements in the soil, NPs are utilized for ensuring nutrients to plants, combat plant ailments, pathogens and detect the presence of trace elements (Khalid *et al*., 2022). As a result of their diminutive size, nanoparticles possess peculiar features compared to bulk materials. Nanoparticles are organic compounds as opposed to individual molecules. Different NPs utilized to treat plants to overcome environmental challenges included TiO_2, Zn, ZnO, Ce, Co, Cu, Se, Ag, Si, Au, SiO_2, FeO, Fe_2O_3, $CaCO_3$, Mg, MgO, Mn etc. These promise to boost crop productivity by enhancing abiotic stress tolerance system in plants. By initiating physiological and biochemical regulation and controlling expression of genes involved in drought tolerance, NPs mitigate effects of drought stress. The root growth instigation, activating aquaporins, altered intracellular water metabolism, accrual of suitable solutes and ionic equilibrium served the primary processes by which NPs reduce osmotic stress resulting from water scarcity. NPs mitigate oxidative stress damage by decreasing ROS and proliferating antioxidant defense systems, hence mitigating leaf water loss induced by increase of ABA through a stomatal constriction (Arif *et al*., 2020).

Salinity is a significant obstacle to modern agriculture and it ultimately deliberates and hinders plant growth and vegetation, leading to death of plants. The incorporation of NPs mitigated destructive effects of salt stress in plants. The foliar application of KNPs to salt-sensitive *Medicago sativa,* enhanced salt tolerance in decreasing electrolyte seepage and increased proline and antioxidant enzyme contents (catalase). Similarly, reduced oxidative stress was demonstrated by declined MDA and ROS levels and increased antioxidant activity in AgNPs-treated pearl millet plants. Cerium-oxide nanoparticles were found to increase photosynthesis in *Brassica napus* via modifying root cells and so enhancing mineral absorption (Al-Khayri *et al*., 2023).

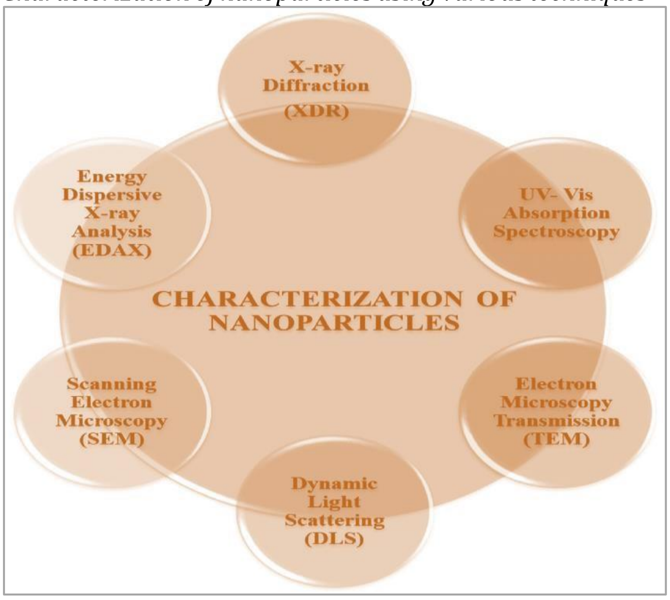
The application of nano-fertilizers proved a viable strategy to addressing soil toxicity and other stress-related issues. The impacts of Si-NPs particles and fertilizers on the morphological and physiological characteristics of basil under salinity stress are considered to be encouraging. Results demonstrated a considerable escalation of growth and development index, chlorophyll content and proline level in basil (*Ocimum basilicum*) treated with Si nanoparticles and silicon fertilizer under salinity. Under salinity stress, the application of Nano-SiO_2 particles revealed a potential increase in chlorophyll content, proline accumulation, leaf fresh and dry weight and antioxidant enzyme action. The application of silicon nanoparticles improves many plant defense systems against salt toxicity (Das and Das, 2019).

Characterization of Nanoparticles

Various characterization techniques have been developed to examine the size, surface charge, distribution, porosity and shape of NPs in different situations. Here, we elaborated the fundamental techniques of characterization (Table 2) of important nanoparticles (Figure 4).

Figure 4

Characterization of nanoparticles using various techniques



Transmission Electron Microscopy

It utilizes a concentrated electron beam on a narrow sample to produce micrographs for nanoscale materials bearing high lateral spatial resolution. By minimizing picture distortion with aberration correctors, contemporary electron microscopes can attain resolutions as low as 0.05–0.1 nm, thereby producing high-resolution images through atomic resolution. By spatial restrictions and focussed impinging beam and calculating the ensuing electron diffraction pattern, TEM also permits the assessment of the crystalline structure of certain microscopic fragments of crystalline materials. Due to its excellent spatial resolution and selectivity, TEM enables the analysis of single-particle size, shape, and crystalline structure. Once a representative batch of nanoparticle sample photos has been taken, the individual size of 1000 particles is determined randomly. In addition to distribution and dispersion, TEM micrographs allow for the visualization of nanoparticle exfoliation, intercalation, and orientation. The TEM offers premium-quality, precise and potent magnification of elemental and complex structures. The disadvantages include lengthy sample preparation, artifacts resulting from sample preparation, its size and cost (Modena *et al*., 2019).

Scanning Electron Microscopy

It creates images of the surface of specimens through scanning it with a high-energy electron beam. When electron beam strikes the surface of specimen and interacts with the atoms of sample, signals in the form of secondary electrons, back-scattered electrons and typical X-rays are produced. These signals carry information pertaining to the surface topography and compositions etc. of samples. It is advantageous having 2-dimensional imaging, easiness of sample preparation and digital data formats. Inappropriate sample preparation might lead to misinterpretation between artefacts and true data, which is one of its shortcomings. And obvious constraints include size, expense and maintenance (Punjabi *et al*., 2015).

Atomic force Microscopy

It is a scanning probe microscopy modus operandi that to capture images of surface of nanometer or even atomic-sized specimens. It is ideally suited for qualitatively evaluating surface roughness and viewing nanoparticle surfaces. It bears significantly higher spatial resolution in three dimensions. Probe is used to scan the sample's surface and oscillation amplitude is utilized to determine the specimen surface properties. It has a sharp tipped end at cantilever that is raster-scanned on the surface of samples and forces are quantified by the cantilever throughout the assessment, consequently its interaction with samples is recorded using a laser beam reflected off the cantilever's tip onto a photodiode array. It may be vertical or lateral deflection of cantilever or transformation of the frequency, amplitude or phase of an oscillating cantilever, depending on the measurement mode. Three distinct modes are typically employed: contact mode, tapping mode and non-contact mode. In contact mode, tip is constantly touched to the specimen's surface. The advantages are AFM offers superior resolution to SEM. Comparable to scanning tunneling microscopy and TEM, it provides genuine atomic resolution. AFM images cannot be scanned as quickly as SEM images, and image artifacts are the limitation (Joshi *et al*., 2008).

X-Ray Diffraction

It is widely employed techniques for characterizing nanoparticles. It typically provides information concerned with the phase nature, lattice parameters, crystalline structure and particle size. Using the Scherrer equation, broadening of the most intense peak of XRD measurement for a particular specimen, the latter parameter is computed. Statistically, representative, volume-averaged values are a benefit of X-ray diffraction procedures, which are often done on powdered samples, typically post-drying the associated colloidal solutions. In comparison to the position and peaks' strength with reference patterns available from the International Centre for Diffraction Data, the database allows for determination of the particle's composition (Mourdikoudis *et al*., 2018).

UV-Vis Spectroscopy

Metal NPs scatter the optical light due to surface plasmon resonance, a collective resonance of the conduction electrons in metals. This SPR peak is visible in these nanoparticles' UV absorption spectra. The magnitude of nanoparticles' peak, spectral bandwidth and wavelengths depends upon their size, shape and material composition. UV-Vis spectroscopy provides a speedy method of examination, a very high degree of precision and accuracy, applies to a large range of substances, and may be utilized both quantitatively and qualitatively. It cannot distinguish between substances absorbing the same wavelengths (Punjabi *et al*., 2015).

Dynamic Light Scattering

The hydrodynamic size and colloidal stability of magnetic nanoparticles with either spherical or anisotropic shapes are monitored using dynamic light scattering. This analytical technique cannot be used alone to offer structural feedback; nevertheless, when combined with other electron microscopy techniques, DLS provides statistically representative data on the hydrodynamic size of nanomaterials. In situ, real-time monitoring of MNP suspension by DLS provides useful information regarding the kinetics of the aggregation process and quantifies the size of the particle clusters created. In addition, DLS is an effective method for measuring the layer thickness of macromolecules adsorbed onto MNP. However, the interpretation of DLS data includes the interaction of several parameters, such as the size, concentration, shape, polydispersity, and surface features of the MNPs involved; hence, rigorous analysis is required to extract the correct data (Lim *et al*., 2013).

Table 2

Characterization of the nanoparticles using different techniques

S. No	Name of nanoparticles	Characterization	Reference
1	Silver (Ag)	XRD DLS-zeta potential	Keskin et al., 2025

		UV–Vis FESEM EDAX FTIR TEM analysis	
2	Gold (Au)	SEM BSE EDS DLS FT-IR spectrum	Alabdallah 2025
3	Zinc (Zn)	UV-Vis spectroscopy TEM XRD EDX SEM	Kamran *et al.*, 2020
4	Iron (Fe)	EDX Zeta potential observations FTIR spectra UV-Vis XRD SEM	Nahari *et al.*, 2022
5	Copper (Cu)	FT-IR SEM-EDS UV-Vis TEM XRD	Amaliyah *et al.*, 2020
6	Palladium (Pd)	LASL HRTEM CW UV-vis spectroscopy TEM	Boutinguiza *et al.* 2016
7	Poly lactic acid (PLA)	ROP	Agusnar *et al.*, 2018
8	Zinc oxide (ZnO)	SEM TEM XRD UV-vis PSA	Talam *et al.*, 2012
9	Silver nitrate ($AgNO_3$)	XRD FT-IR HRTEM TEM	Thiruvengadam and Bansod, 2020
10	Titanium oxide (Ti_2O_3)	XRD TEM	Li *et al.*, 2022
11	Platinum (Pt)	TEM FE-SEM	Ali and Mohammed, 2021
12	Lutetium oxide (Lu_2O_3)	OACS XRD TEM	Barrera *et al.*, 2010
13	Ferric oxide (Fe_3O_4)	FTIR XRD FESEM AFM	Takai *et al.*, 2019
14	Manganese oxide (MnO_3)	XRD TEM FTIR	Selvam *et al.*, 2015
15	Silicon dioxide (SiO_2)	CMP	Kao *et al.*, 2014
16	Silicon (Si)	TEM	Yue et al., 2025

Abbreviations: Laser Ablation of Solids (LASL), Field Emission Scanning Electron Microscope (FESEM), Ultraviolet-visible spectroscopy (UV-Vis spectroscopy), Energy dispersive X-ray (EDX), Scanning electron microscopy (SEM), X-ray diffraction analysis (XRD), Backscattered electrons (BSE), Dynamic light scattering (DLS), Fourier-transform infrared spectroscopy (FTIR), Continuous wave (CW), Transmission electron microscopy (TEM), Chemical mechanical polishing Technology (CMP), Ring-Opening Polymerization (ROP), High-resolution transmission electron microscopy (HRTEM), Photoluminescence spectroscopy analysis (PSA), Optical absorption and cathodoluminescence spectra (OACS), Atomic Force Microscopy (AFM).

CONCLUSION

Abiotic stressors diminished the development, growth and production of plants. To cope with this issue, the scientific community is attempting to devise alternatives of nanoparticles, that are more sustainable and won't have a significant effect on the surrounding ecosystem. The increasing demand for nanotechnology prompted the development of green synthetic methods for producing NPs from plants, microorganisms and other natural resources. These are eco-friendly substances, easily available, cost-effective, non-toxic and effective substances. The plants usage for synthesis of green nanoparticles is an intriguing and emerging area of nanotechnology bearing a significant impact on the ecosystem, adding to their long-term sustainability and development. The application of NPs dramatically enhanced the abiotic stress tolerance of plants by enhancing cellular antioxidants, photosynthetic efficiency, nutrient absorption and biochemical/molecular mechanism regulation. Although nano-fertilizers provide a cost-effective method for enhancing the abiotic stress tolerance of plants by supplying necessary nutrients, their widespread use has raised concerns about their potentially harmful impacts on the environment. Thus, the biogenic NPs serve as a fascinating and developing component of nanotechnology, contributing significantly to the development of future research and sustainable agriculture around the world.

REFERENCES

Abbas, S., Nasreen, S., Haroon, A., & Ashraf, M. A. (2020). Synthesis of silver and copper nanoparticles from plants and application as adsorbents for naphthalene decontamination. *Saudi Journal of Biological Sciences*, *27*(4), 1016-1023. https://doi.org/10.1016/j.sjbs.2020.02.011

Abobatta, W. F. (2018). Nanotechnology application in agriculture. *Acta Scientific Agriculture*, *2*(6), 99-102. https://sazokesht.com/wp-content/uploads/2023/08/Nanotechnology-in-agriculture.pdf

Acharya, C., Chaurasia, S. K., Pandey, J. K., & Shakya, V. S. (2025). Portulaca oleracea-mediated green synthesis of ZnO nanoparticles, characterization and assessment of their antibacterial, dye degradation, and chilling stress mitigation potential in wheat seedling. *Inorganic Chemistry Communications*, *180*, 114960. https://doi.org/10.1016/j.inoche.2025.114960

Agrawal, S., & Rathore, P. (2014). Nanotechnology pros and cons to agriculture: a review. *Int J Curr Microbiol App Sci*, *3*(3), 43-55. http://www.ijcmas.com/vol-3-3/Shweta%20Agrawal%20and%20Pragya%20Rathore.pdf

Agusnar, H., Wirjosentono, B., Rihayat, T., & Salisah, Z. (2018). Synthesis and characterization of poly (lactic acid)/chitosan nanocomposites based on renewable resources as biobased-material. In *Journal of Physics: Conference Series* (Vol. 953, No. 1, p. 012015). IOP Publishing.

Alabdallah, N. M. (2025). Do gold nanoparticles consistently benefit crop plants under both non-stressed and abiotic stress conditions? *Nanotechnology Reviews*, *14*(1). https://doi.org/10.1515/ntrev-2025-0153

Ali, N. H., & Mohammed, A. M. (2021). Biosynthesis and characterization of platinum nanoparticles using Iraqi Zahidi dates and evaluation of their biological applications. *Biotechnology Reports*, *30*, e00635. https://doi.org/10.1016/j.btre.2021.e00635

Al-Khayri, J. M., Rashmi, R., Surya Ulhas, R., Sudheer, W. N., Banadka, A., Nagella, P., Aldaej, M. I., Rezk, A. A., Shehata, W. F., & Almaghasla, M. I. (2023). The role of nanoparticles in response of plants to abiotic stress at physiological, biochemical, and molecular levels. *Plants*, *12*(2), 292. https://doi.org/10.3390/plants12020292

Amaliyah, S., Pangesti, D. P., Masruri, M., Sabarudin, A., & Sumitro, S. B. (2020). Green synthesis and characterization of copper nanoparticles using piper retrofractum Vahl extract as bioreductor and capping agent. *Heliyon*, *6*(8), e04636. https://doi.org/10.1016/j.heliyon.2020.e04636

Anandalakshmi, K., Venugobal, J., & Ramasamy, V. (2015). Characterization of silver nanoparticles by green synthesis method using Pedalium murex leaf extract and their antibacterial activity. *Applied Nanoscience*, *6*(3), 399-408. https://doi.org/10.1007/s13204-015-0449-z

Anon, T., Das, A., Thakur, S., Ruchika, K., Choudhary, K., & Anon, K. (2022). Nanoparticles: Applications in medicine and agriculture. *International Journal of Scientific and Research Publications (IJSRP)*, *12*(3), 28. https://doi.org/10.29322/ijsrp.12.03.2022.p12306

Arif, Y., Singh, P., Siddiqui, H., Bajguz, A., & Hayat, S. (2020). Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. *Plant Physiology and Biochemistry*, *156*, 64-77. https://doi.org/10.1016/j.plaphy.2020.08.042

Arora, P. K., Tripathi, S., Omar, R. A., Chauhan, P., Sinhal, V. K., Singh, A., Srivastava, A., Garg, S. K., & Singh, V. P. (2024). Next-generation fertilizers: The impact of bionanofertilizers on sustainable agriculture. *Microbial Cell Factories*, *23*(1). https://doi.org/10.1186/s12934-024-02528-5

Atanda, S. A., Shaibu, R. O., & Agunbiade, F. O. (2025). Nanoparticles in agriculture: Balancing food security and environmental sustainability. *Discover Agriculture*, *3*(1). https://doi.org/10.1007/s44279-025-00159-x

Balamurugan, M., Venkatesan, G., Ramachandran, S., & Saravanan, S. (2015). synthesis and characterization of Manganese Oxide nanoparticles. *Synthesis and Fabrication of Nanomaterials*, 311-314.

Bao, Y., He, J., Song, K., Guo, J., Zhou, X., & Liu, S. (2021). Plant-extract-Mediated synthesis of metal nanoparticles. *Journal of Chemistry*, *2021*, 1-14. https://doi.org/10.1155/2021/6562687

Barrera, E. W., Cascales, C., Pujol, M. C., Park, K. H., Choi, S. B., Rotermund, F., Carvajal, J. J., Mateos, X., Aguiló, M., & Díaz, F. (2010). Synthesis of Tm:Lu2O3 nanocrystals for phosphor blue applications. *Physics Procedia*, *8*, 142-150. https://doi.org/10.1016/j.phpro.2010.10.025

Begum, S. R., Rao, D. M., & Reddy, P. D. (2018). Role of green route synthesized silver nanoparticles in medicinal applications with special reference to cancer therapy. *Biosciences Biotechnology Research Asia*, *15*(4), 783-790. https://doi.org/10.13005/bbra/2686

Boutinguiza, M., Meixus, M., Del Val, J., Riveiro, A., Comesaña, R., Lusquiños, F., & Pou, J. (2016). Synthesis and characterization of PD nanoparticles by laser ablation in water using nanosecond laser. *Physics Procedia*, *83*, 36-45. https://doi.org/10.1016/j.phpro.2016.08.005

Buarki, F., AbuHassan, H., Al Hannan, F., & Henari, F. Z. (2022). Green synthesis of iron oxide nanoparticles using hibiscus Rosa sinensis flowers and their antibacterial activity. *Journal of Nanotechnology*, *2022*, 1-6. https://doi.org/10.1155/2022/5474645

Chakraborty, S., Singh, A., & Roychoudhury, A. (2022). Biogenic nanoparticles and generation of abiotic stress-resilient plants: A new approach for sustainable agriculture. *Plant Stress*, *6*, 100117. https://doi.org/10.1016/j.stress.2022.100117

Das, A., & Das, B. (2019). Nanotechnology a potential tool to mitigate abiotic stress in crop plants. *Abiotic and Biotic Stress in Plants*. https://doi.org/10.5772/intechopen.83562

Dey, N., Vinayagam, S., Kamaraj, C., Gnanasekaran, L., Goyal, K., Ali, H., ... & Subramaniyan, V. (2025). Ecotoxicological evaluation of nanosized particles with emerging contaminants and their impact assessment in the aquatic environment: a review. *Journal of Nanoparticle Research*, *27*(4), 1-21. https://doi.org/10.1007/s11051-025-06306-1

Fahmy, S. A., Preis, E., Bakowsky, U., & Azzazy, H. M. (2020). Platinum nanoparticles: Green synthesis and biomedical applications. *Molecules*, *25*(21), 4981. https://doi.org/10.3390/molecules25214981

Ghidan, A. Y., & Al Antary, T. M. (2020). Applications of nanotechnology in agriculture. *Applications of Nanobiotechnology*. https://doi.org/10.5772/intechopen.88390

González-Moscoso, M., Martínez-Villegas, N., Cadenas-Pliego, G., & Juárez-Maldonado, A. (2022). Effect of silicon nanoparticles on tomato plants exposed to two forms of inorganic arsenic. *Agronomy*, *12*(10), 2366. https://doi.org/10.3390/agronomy12102366

Goswami, P., Yadav, S., & Mathur, J. (2019). Positive and negative effects of nanoparticles on plants and their applications in agriculture. *Plant Science Today*, *6*(2), 232-242. https://doi.org/10.14719/pst.2019.6.2.502

Hano, C., & Abbasi, B. H. (2021). Plant-based green synthesis of nanoparticles: Production, characterization and applications. *Biomolecules*, *12*(1), 31. https://doi.org/10.3390/biom12010031

Iljkić, D., Rastija, M., Šimić, D., Lončarić, Z., Drenjančević, L., Zebec, V., Samfira, I., Zoican, C., & Varga, I. (2025). Effects of extreme combined abiotic stress on yield and quality of maize hybrids. *Agronomy*, *15*(6), 1440. https://doi.org/10.3390/agronomy15061440

Imran, Q. M., Falak, N., Hussain, A., Mun, B., & Yun, B. (2021). Abiotic stress in plants; Stress perception to molecular response and role of biotechnological tools in stress resistance. *Agronomy*, *11*(8), 1579. https://doi.org/10.3390/agronomy11081579

Jadhao, A. D., Shende, S., Ingle, P., Gade, A., Hajare, S. W., & Ingole, R. S. (2020). Biogenic synthesis of zinc oxide nanoparticles by*Bryophyllum pinnatum*and its acute oral toxicity evaluation in Wistar rats. *IEEE Transactions on NanoBioscience*, *19*(4), 633-639. https://doi.org/10.1109/tnb.2020.3014023

Jadoun, S., Arif, R., Jangid, N. K., & Meena, R. K. (2020). Green synthesis of nanoparticles using plant extracts: A review. *Environmental Chemistry Letters*, *19*(1), 355-374. https://doi.org/10.1007/s10311-020-01074-x

Joshi, M., Bhattacharyya, A., & Ali, S. W. (2008). Characterization techniques for nanotechnology applications in textiles. *Indian J. Fibre Text. Res*, *33*(3), 304-317.

Kamalakaran, R., Singh, A. K., & Srivastava, O. N. (1995). Formation and characterization of silicon nanoparticles-threads, tubules and possibly silicon fullerene-like structures. *Journal of Physics: Condensed Matter*, *7*(41), L529-L535. https://doi.org/10.1088/0953-8984/7/41/001

Kao, M. J., Hsu, F. C., & Peng, D. X. (2014). Synthesis and characterization of nanoparticles and Their Efficacy in Chemical Mechanical Polishing Steel Substrate. *Advances in Materials Science and Engineering*, *2014*, 1-8. https://doi.org/10.1155/2014/691967

Karthik Raja, R., Prabu Kumar, S., Balasubramani, G., Sankaranarayanan, C., Liu, B., Hazir, S., & Narayanan, M. (2025). An updated review on green synthesized nanoparticles to control insect pests. *Journal of Pest Science*, *98*(1), 31-50. https://doi.org/10.1007/s10340-024-01863-1

Keskin, C., Aslan, S., Baran, M. F., Baran, A., Eftekhari, A., Adıcan, M. T., ... & Mohamed, A. J. (2025). Green synthesis and characterization of silver nanoparticles using anchusa officinalis: antimicrobial and cytotoxic potential. *International Journal of Nanomedicine*, 4481-4502. https://doi.org/10.2147/IJN.S511217

Khalid, M. F., Iqbal Khan, R., Jawaid, M. Z., Shafqat, W., Hussain, S., Ahmed, T., Rizwan, M., Ercisli, S., Pop, O. L., & Alina Marc, R. (2022). Nanoparticles: The plant saviour under abiotic stresses. *Nanomaterials*, *12*(21), 3915. https://doi.org/10.3390/nano12213915

Khan, F., Pandey, P., & Upadhyay, T. K. (2022). Applications of nanotechnology-based agrochemicals in food security and sustainable agriculture: An overview. *Agriculture*, *12*(10), 1672. https://doi.org/10.3390/agriculture12101672

Khanal, L. N., Sharma, K. R., Paudyal, H., Parajuli, K., Dahal, B., Ganga, G. C., Pokharel, Y. R., & Kalauni, S. K. (2022). Green synthesis of silver nanoparticles from root extracts of *Rubus ellipticus* Sm. and comparison of antioxidant and antibacterial activity. *Journal of Nanomaterials*, *2022*(1). https://doi.org/10.1155/2022/1832587

Kumar, A., Kumari, D., Adarsh, A., & Solankey, S. S. (2025). Advances in abiotic stresses management in potatoes. *Advances in Olericulture*, 297-343. https://doi.org/10.1007/978-3-031-82710-5_14

Kumar, H., Bhardwaj, K., Kuča, K., Kalia, A., Nepovimova, E., Verma, R., & Kumar, D. (2020). Flower-based green synthesis of metallic nanoparticles: Applications beyond fragrance. *Nanomaterials*, *10*(4), 766. https://doi.org/10.3390/nano10040766

Kumar, S. (2020). Abiotic stresses and their effects on plant growth, yield and nutritional quality of agricultural produce. *International Journal of Food Science and Agriculture*, *4*(4), 367-378. https://doi.org/10.26855/ijfsa.2020.12.002

Kumari, A., Kumar, V., & Yadav, S. K. (2012). Plant extract synthesized PLA nanoparticles for controlled and sustained release of quercetin: a green approach. *PLoS one*, *7*(7), e41230. https://doi.org/10.1371/journal.pone.0041230

Kuppusamy, P., Yusoff, M. M., Maniam, G. P., & Govindan, N. (2016). Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications – An updated report. *Saudi Pharmaceutical Journal*, *24*(4), 473-484. https://doi.org/10.1016/j.jsps.2014.11.013

Li, W., Feng, W., Wu, S., Wang, W., & Yu, D. (2022). Synergy of photothermal effect in integrated 0D Ti2O3 nanoparticles/1D carboxylated carbon nanotubes for multifunctional water purification. *Separation and Purification Technology*, *292*, 120989. https://doi.org/10.1016/j.seppur.2022.120989

Lim, J., Yeap, S. P., Che, H. X., & Low, S. C. (2013). Characterization of magnetic nanoparticle by dynamic light scattering. *Nanoscale Research Letters*, *8*(1). https://doi.org/10.1186/1556-276x-8-381

Liu, C., Zhou, H., & Zhou, J. (2021). The applications of nanotechnology in crop production. *Molecules*, *26*(23), 7070. https://doi.org/10.3390/molecules26237070

Mamatha, G., Sowmya, P., Madhuri, D., Mohan Babu, N., Suresh Kumar, D., Vijaya Charan, G., Varaprasad, K., & Madhukar, K. (2020). Antimicrobial cellulose Nanocomposite films with in situ generations of bimetallic (Ag and CU) nanoparticles using Vitex negundo leaves extract. *Journal of Inorganic and Organometallic Polymers and Materials*, *31*(2), 802-815. https://doi.org/10.1007/s10904-020-01819-9

Manzoor, N., Ali, L., Ahmed, T., Noman, M., Adrees, M., Shahid, M. S., Ogunyemi, S. O., Radwan, K. S., Wang, G., & Zaki, H. E. (2022). Recent advancements and development in nano-enabled agriculture for improving abiotic stress tolerance in plants. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.951752

Modena, M. M., Rühle, B., Burg, T. P., & Wuttke, S. (2019). Nanoparticle characterization: Nanoparticle characterization: What to measure? (Adv. Mater. 32/2019). *Advanced Materials*, *31*(32). https://doi.org/10.1002/adma.201970226

Mohammed, M. M. (2021). Disadvantages of using nano-particles as fertilizers in Iraq. *IOP Conference Series: Earth and Environmental Science*, *735*(1), 012043. https://doi.org/10.1088/1755-1315/735/1/012043

Mourdikoudis, S., Pallares, R. M., & Thanh, N. T. (2018). Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties. *Nanoscale*, *10*(27), 12871-12934. https://doi.org/10.1039/C8NR02278J

Murthy, H. A., Desalegn, T., Kassa, M., Abebe, B., & Assefa, T. (2020). Synthesis of green copper nanoparticles using medicinal plant Hagenia abyssinica (Brace) JF. Gmel. leaf extract: Antimicrobial properties. *Journal of nanomaterials*, *2020*(1), 3924081. https://doi.org/10.1155/2020/3924081

Nahari, M. H., Al Ali, A., Asiri, A., Mahnashi, M. H., Shaikh, I. A., Shettar, A. K., & Hoskeri, J. (2022). Green synthesis and characterization of iron nanoparticles synthesized from aqueous leaf extract of Vitex leucoxylon and its biomedical applications. *Nanomaterials*, *12*(14), 2404. https://doi.org/10.3390/nano12142404

Naseer, M., Aslam, U., Khalid, B., & Chen, B. (2020). Green route to synthesize Zinc Oxide Nanoparticles using leaf extracts of Cassia fistula and Melia azadarach and their antibacterial potential. *Scientific Reports*, *10*(1), 9055. https://doi.org/10.1038/s41598-020-65949-3

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), e05981. https://doi.org/10.1016/j.heliyon.2021.e05981

Punjabi, K., Choudhary, P., Samant, L., Mukherjee, S., Vaidya, S., & Chowdhary, A. (2015). Biosynthesis of nanoparticles: a review. *Int. J. Pharm. Sci. Rev. Res*, *30*(1), 219-26.

Rawat, A. K., & Tripathi, U. K. (2020). Advances in Agronomy, Vol-9, Akinik Publishers, New Delhi, India.

Ray, A., Das, P., Chunduri, R., Kumar, D., Dulta, K., Kaushal, A., Gupta, S., RJ, S., Yadav, A. N., Nagraik, R., & Sharma, A. (2025). Nanocomposite-based agricultural delivery systems: A sustainable approach to enhanced crop productivity and soil health. *Journal of Nanoparticle Research*, *27*(4). https://doi.org/10.1007/s11051-025-06302-5

Rehmanullah, Muhammad, Z., Inayat, N., & Majeed, A. (2020). Application of nanoparticles in agriculture as fertilizers and pesticides: Challenges and opportunities. *New Frontiers in Stress Management for Durable Agriculture*, 281-293. https://doi.org/10.1007/978-981-15-1322-0_17

Rouphael, Y., Petropoulos, S. A., Cardarelli, M., & Colla, G. (2018). Salinity as eustressor for enhancing quality of vegetables. *Scientia Horticulturae*, *234*, 361-369. https://doi.org/10.1016/j.scienta.2018.02.048

Rudra, S., & Kingsley, D. (2025). The Nano Revolution, Metal Nanoparticles in Antibiotic-Resistant Era: Synthesis, Properties, and Antimicrobial Applications. In *Innovations and Applications of Advanced Biomaterials in Healthcare and Engineering* (pp. 91-142). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3373-1305-4.ch003

Saha, R., Subramani, K., Sikdar, S., Fatma, K., & Rangaraj, S. (2021). Effects of processing parameters on green synthesised ZnO nanoparticles using stem extract of Swertia chirayita. *Biocatalysis and Agricultural Biotechnology*, *33*, 101968. https://doi.org/10.1016/j.bcab.2021.101968

Saif, S., Tahir, A., & Chen, Y. (2016). Green synthesis of iron nanoparticles and their environmental applications and implications. *Nanomaterials*, *6*(11), 209. https://doi.org/10.3390/nano6110209

Selye, H. (1946). Nature 36. Pdf. *Nature*.

Sethy, N. K., Arif, Z., Mishra, P. K., & Kumar, P. (2020). Green synthesis of TiO2 nanoparticles from Syzygium cumini extract for photo-catalytic removal of lead (PB) in explosive industrial wastewater. *Green Processing and Synthesis*, *9*(1), 171-181. https://doi.org/10.1515/gps-2020-0018

Shahid, M., Khalid, S., Abbas, G., Shahid, N., Nadeem, M., Sabir, M., Aslam, M., & Dumat, C. (2015). Heavy metal stress and crop productivity. *Crop Production and Global Environmental Issues*, 1-25. https://doi.org/10.1007/978-3-319-23162-4_1

Siddiqi, K. S., & Husen, A. (2016). Green synthesis, characterization and uses of palladium/Platinum nanoparticles. *Nanoscale Research Letters*, *11*(1). https://doi.org/10.1186/s11671-016-1695-z

Siddiqui, M. H., Al-Whaibi, M. H., Firoz, M., & Al-Khaishany, M. Y. (2015). Role of nanoparticles in plants. *Nanotechnology and Plant Sciences*, 19-35. https://doi.org/10.1007/978-3-319-14502-0_2

Singh, J., Dutta, T., Kim, K., Rawat, M., Samddar, P., & Kumar, P. (2018). 'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *Journal of Nanobiotechnology*, *16*(1). https://doi.org/10.1186/s12951-018-0408-4

Sobczak-Kupiec, A., Malina, D., Zimowska, M., & Wzorek, Z. (2011). Characterization of gold nanoparticles for various medical application. *Dig J Nanomater Bios*, *6*(2), 803-808. https://www.chalcogen.ro/803_Kupiec.pdf

Takai, Z., Mustafa, M., & Asman, S. (2018). Preparation of high performance conductive Polyaniline magnetite (PANI/Fe3O4) Nanocomposites by Sol-gel method. *Asian Journal of Chemistry*, *30*(12), 2625-2630. https://doi.org/10.14233/ajchem.2018.21473

Talam, S., Karumuri, S. R., & Gunnam, N. (2012). Synthesis, characterization, and spectroscopic properties of ZnO nanoparticles. *International Scholarly Research Notices*, *2012*(1), 372505. https://doi.org/10.5402/2012/372505

Tariq, M., Choudhary, S., Singh, H., Asif Siddiqui, M., Kumar, H., Amir, A., & Kapoor, N. (2021). Role of nanoparticles in abiotic stress. *Technology in Agriculture*. https://doi.org/10.5772/intechopen.99928

Thiruvengadam, V., & Bansod, A. V. (2020). Characterization of silver nanoparticles synthesized using chemical method and its antibacterial property. *Biointerface Res. Appl. Chem*, *10*(6), 7257-7264. https://doi.org/10.33263/BRIAC106.72577264

Toscano, S., Trivellini, A., Cocetta, G., Bulgari, R., Francini, A., Romano, D., & Ferrante, A. (2019). Effect of Preharvest abiotic stresses on the accumulation of Bioactive compounds in horticultural produce. *Frontiers in Plant Science*, *10*. https://doi.org/10.3389/fpls.2019.01212

Vannini, C., Domingo, G., Onelli, E., Prinsi, B., Marsoni, M., Espen, L., & Bracale, M. (2013). Morphological and Proteomic responses of eruca sativa exposed to silver nanoparticles or silver nitrate. *PLoS ONE*, *8*(7), e68752. https://doi.org/10.1371/journal.pone.0068752

Yu, W., Tang, J., Gao, C., Zheng, X., & Zhu, P. (2025). Green synthesis of copper nanoparticles from the aqueous extract of lonicera japonica Thunb and evaluation of its catalytic property and cytotoxicity and antimicrobial activity. *Nanomaterials*, *15*(2), 91. https://doi.org/10.3390/nano15020091

Yue, Q., Wen, J., Zhou, Y., & Zheng, Y. (2025). Resource utilization of waste solar photovoltaic panels for preparation of microporous silicon nanoparticles. *Waste Management*, *193*, 495-505. https://doi.org/10.1016/j.wasman.2024.12.039

Zhan, X., & Zhu, Y. (2025). Abiotic stress and mechanisms of stress tolerance in vegetable crops. *Growth Regulation and Quality Improvement of Vegetable Crops*, 183-224. https://doi.org/10.1007/978-981-96-0169-1_8