REVIEW ARTICLE

Mechanisms of Abiotic Stress Mitigation in Plants Using Biologically Synthesized Nanoparticles. A review

Pukraj Ud Din[1]*, Abdul Qadir[2], Aneela Riaz[3], Ibrahim[1], Faizan Ahmad[4], Muhammad Asim Khan[5]

[1]Department of Chemistry, Government Degree College Tangi, Bacha Khan University Charsadda, Pakistan
[2]Department of plant breeding and genetics, Sindh agricultural university Tandojam, Pakistan
[3]Institute of Pure and Applied Biology Bahauddinn Zakriya University Multan, Pakistan
[4]The Quaid e Azam College for boys Mardan, Pakistan
[5]Islamia college Peshawar, Pakistan

Corresponding author: Pukraj Ud Din. Email: pukrajchemist@gmail.com
Received: 03 June, 2025, Accepted: 27 June, 2025, Published: 30 June, 2025

Abstract
Abiotic stresses such as drought, salinity, extreme temperatures, and heavy metal toxicity significantly limit plant growth, productivity, and global food security. Conventional management strategies, including breeding, chemical amendments, and irrigation practices, often fail to provide sustainable and long-term protection. In recent years, biologically synthesized nanoparticles (NPs) have emerged as eco-friendly tools for enhancing plant tolerance to environmental stress. These biogenic nanoparticles, produced using plants, microbes, fungi, and algae, possess unique physicochemical and biocompatible properties that enable targeted interactions within plant systems. Their application improves antioxidant defense by enhancing the activity of enzymes responsible for reactive oxygen species scavenging, regulates stress-responsive genes, and increases photosynthetic efficiency under adverse conditions. Furthermore, biogenic nanoparticles promote osmolyte accumulation, nutrient uptake, and ion homeostasis, thereby strengthening plant resilience against salinity, drought, and heavy metal toxicity. Compared with chemically synthesized nanoparticles, biological synthesis offers advantages such as lower toxicity, environmental safety, and greater compatibility with plant tissues. This review summarizes the synthesis approaches, mechanisms of action, and recent advances related to the use of biogenic nanoparticles for mitigating abiotic stress in plants. Additionally, it highlights current knowledge gaps related to molecular interactions, environmental fate, and field-level validation. Future research priorities include integrating nano-enabled tools into sustainable agriculture, optimizing dosage and application methods, and evaluating long-term ecological impacts. Biologically synthesized nanoparticles represent a promising frontier for developing climate-resilient and resource-efficient agricultural strategies.

Keywords: Biogenic nanoparticles; Abiotic stress; Salinity; Drought; Temperature

Introduction

Nanotechnology has rapidly emerged as one of the most transformative areas of modern science, offering groundbreaking opportunities across disciplines such as biotechnology, materials science, medicine, and agriculture (Bajpai et al. 200). It involves the design, synthesis, and application of materials with dimensions ranging from 1 to 100 nanometers, where matter exhibits novel optical, electrical, and biological properties distinct from its bulk counterparts (Khan and Bano 2016). The application of nanotechnology in agriculture has opened new avenues for improving crop productivity, stress tolerance, and sustainability in food production systems (Gopinath et al., 2012). The 21st century has seen an alarming increase in abiotic stresses such as drought, salinity, extreme temperatures, and heavy metal contamination, which drastically reduce crop yield and threaten global food security (Khan et al. 2020). Traditional methods such as breeding for stress-tolerant varieties, the application of fertilizers, or irrigation management have proven insufficient to overcome these multifaceted challenges (Noor et al. 2022). Therefore, the integration of nanotechnology into plant sciences has gained momentum as a promising approach to enhance plant resilience and productivity under adverse environmental conditions (Mohammadlou et al 2026). Conventional nanoparticle synthesis methods, including chemical reduction, electrochemical deposition, and photochemical approaches, often involve toxic reagents and high energy consumption, posing serious risks to human health and the environment (Ali et al., 2021). To address these challenges, green nanotechnology has emerged as a sustainable and eco-friendly alternative that relies on biological systems such as plants, bacteria, fungi, and algae for nanoparticle biosynthesis (Mubraiz et al., 201). The biological synthesis process is driven by the natural reducing and stabilizing agents present in biomolecules like proteins, enzymes, flavonoids, phenolics, alkaloids, terpenoids, and polysaccharides (Elmer and White 2018). Among these biological routes, plant-mediated synthesis is particularly advantageous due to its simplicity, scalability, and rapid reaction rates (Noor et al., 2022). Plant extracts contain diverse secondary metabolites that act as both reducing and capping agents, ensuring stability and controlled particle size during synthesis (Worrall et al., 2018). Moreover, the process eliminates the need for microbial culture maintenance or sterile conditions, making it highly cost-effective and suitable for large-scale applications (Sattar et al., 2022). The nanoparticles produced through such methods, often termed biogenic nanoparticles, display enhanced biocompatibility, stability, and catalytic potential, rendering them ideal for agricultural applications (Sun et al., 2022). Various metallic and metal oxide nanoparticles such as silver (Ag), gold (Au), zinc oxide (ZnO), titanium dioxide (TiO_2), and iron oxide (Fe_2O_3) have been synthesized using biological methods (Iqbal et al., 2021). The synthesis parameters, including pH, temperature, precursor concentration, and biological extract composition, significantly influence the morphology, size, and surface charge of nanoparticles (Yin et al., 2003). Characterization techniques such as UV–Visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), transmission electron microscopy (TEM), and dynamic light scattering (DLS) are widely employed to determine the physicochemical properties of these nanoparticles (Dimitrijevic et al., 2001). Biologically synthesized nanoparticles demonstrate unique surface reactivity, high surface area-to-volume ratios, and remarkable stability in aqueous environments (Callegari et al., 2003). These properties enable them to interact efficiently with plant systems, facilitating targeted delivery of nutrients, enhancement of photosynthesis, and modulation of biochemical pathways under stress conditions (Zhang et al., 2006). Abiotic stresses disrupt plant homeostasis by inducing excessive accumulation of reactive oxygen species (ROS), impairing photosynthesis, and disturbing nutrient balance (Swami et al., 2004). Biogenic nanoparticles help mitigate these damages through various mechanisms. For instance, ZnO and Fe_2O_3 nanoparticles act as micronutrient supplements, enhancing chlorophyll synthesis and antioxidant enzyme activities (Masood et al., 2021). Silver nanoparticles (AgNPs) and silicon nanoparticles (SiNPs) enhance the expression of stress-responsive genes, strengthen cellular membranes, and improve water retention under drought conditions (Naik et al., 2002). Additionally, nanoparticles can activate molecular signaling cascades such as abscisic acid (ABA) and mitogen-activated protein kinase (MAPK) pathways, which regulate stress responses at the transcriptional level (Sastry et al., 2003). Moreover, biologically synthesized nanoparticles contribute to ionic homeostasis under salinity stress by balancing Na^+ and K^+ concentrations, thus protecting photosynthetic machinery and maintaining osmotic equilibrium (Zare et al., 2013).

They also assist in the chelation and detoxification of heavy metals, reducing their phytotoxic effects while improving nutrient assimilation (Hu et al., 2005). e integration of nanotechnology into sustainable agriculture aligns with the principles of green chemistry and environmental protection (Kim et al., 2007). Biogenic nanoparticles not only enhance plant tolerance to abiotic stresses but also reduce dependence on chemical fertilizers and pesticides (Lu et al., 2007). By acting as nano-carriers, they allow controlled release and targeted delivery of agrochemicals, minimizing environmental pollution and improving efficiency (Mohammadi et al., 2019). Furthermore, biological synthesis ensures that the nanoparticles are biodegradable, non-toxic, and less likely to accumulate in soil and water ecosystems (Soleimani, and Habibi-Pirkoohi 2017). Despite these advantages, challenges remain in understanding nanoparticle–plant interactions at molecular, cellular, and ecological levels. Variations in nanoparticle properties, plant species, and environmental conditions can lead to diverse physiological responses (Bajpai et al., 2007). Therefore, systematic studies on the long-term environmental fate, bioaccumulation potential, and ecotoxicological impacts of biogenic nanoparticles are urgently needed (Maheswari, et al., 2012). This review focuses on the mechanisms through which biologically synthesized nanoparticles mitigate abiotic stresses in plants. It provides a detailed overview of biological synthesis pathways, characterization techniques, and their applications in improving plant physiological and molecular responses under stress. The paper also highlights the underlying cellular signaling pathways, including antioxidant defense mechanisms, ion regulation, and gene expression modulation. Lastly, it outlines future research directions emphasizing sustainable applications, biosafety assessment, and regulatory frameworks essential for integrating nanotechnology into environmentally responsible agriculture. By bridging nanotechnology with plant stress biology, this review aims to contribute to the development of climate-resilient and sustainable agricultural systems, offering a scientific foundation for next-generation crop improvement strategies.

In recent years, the synthesis and study of nanoparticles has gained remarkable attention from scientists engaged in both basic and applied research. Metal nanoparticles (MNPs) are considered a key class within engineered nanomaterials. These nanoparticles (such as silver, gold, and copper) have attracted widespread interest because of their unique electronic, catalytic, magnetic, and optical properties. They are particularly valuable in applications like biosensing, bio-conjugation, catalysis, drug delivery, imaging, and surface-enhanced Raman spectroscopy. Recently, a wide range of synthetic methods for the preparation of MNPs has been established, including chemical, photochemical, electrochemical, and thermal approaches. However, among these, growing emphasis is placed on biological and green technologies for nanoparticle production due to their safer and eco-friendly nature (Yin et al., 2003). Within MNPs, silver nanoparticles (AgNPs) hold a crucial role in biology, medicine, and agriculture. They have gained increasing importance because of their strong surface plasmon resonance (Noor et al., 2022), optical features (Dimitrijevic et al., 2001), catalytic performance (Callegari et al., 2003), excellent antimicrobial activity (Zhang et al., 2006). anticancer potential, and even wound-healing applications (Naik et al., 2002). In recent studies, AgNPs have also shown promise in water purification, biosensor development, crop disease control, and pharmaceutical formulations. Their multifunctional roles highlight their potential beyond traditional biomedical uses. Although many methods exist for synthesizing MNPs, the chemical reduction of metal ions followed by stabilization is most commonly used (Sastry et al., 2003). However, these processes are costly, often involve hazardous chemicals, and may generate harmful by-products, raising environmental and biological safety concerns. This has led scientists and nanochemists to explore green, low-cost, and scalable alternatives. Nanobiotechnology provides new solutions by synthesizing nanostructures through living organisms. Among biological methods, plants have emerged as particularly promising tools in the synthesis of MNPs. Unlike microbial systems, plant-based synthesis avoids the complexity of culture maintenance while ensuring rapid, stable, and cost-effective production. Plant extracts contain diverse phytochemicals such as flavonoids, alkaloids, phenolics, terpenoids, and proteins, which act as natural reducing and stabilizing agents.

These biomolecules not only facilitate extracellular nanoparticle synthesis but also allow precise control over size, shape, and dispersion. Such controlled biosynthesis ensures improved reproducibility and functional efficiency of nanoparticles. Furthermore, the use of plants for nanoparticle synthesis can be scaled up to meet industrial requirements, making them suitable for large-scale production (Zare et al., 2013). The integration of plant-mediated biosynthesis with modern nanotechnology could pave the way for sustainable nanomaterials that serve in agriculture, medicine, food preservation, and environmental remediation. Green synthesis utilizes biological extracts like plants or microbes as reducing agents, offering an eco-friendly and biocompatible route. In contrast, chemical synthesis employs synthetic reagents for precise control over size and shape, but often involves toxic chemicals and higher energy consumption, posing environmental concerns Figure 1.

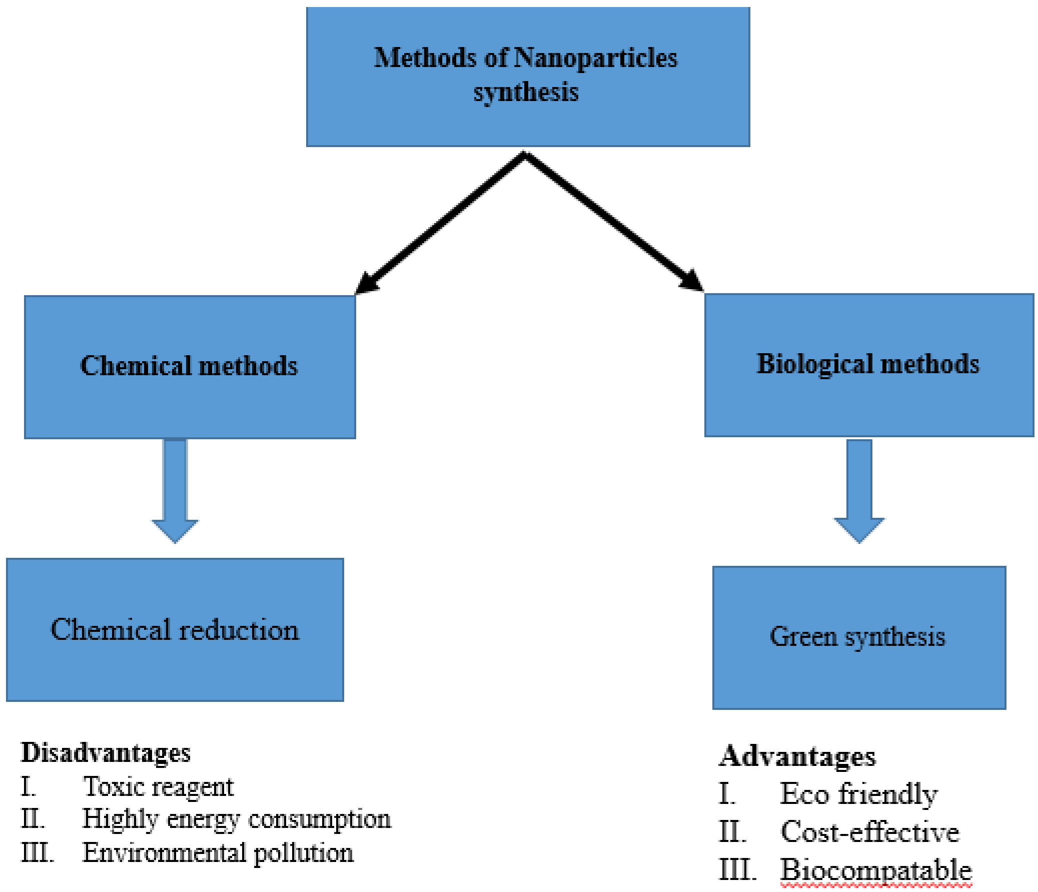

Figure 1: Comparative overview of nanoparticle synthesis approaches

Methods of Synthesis of Nanoparticles

Biogenic-Mediated Synthesis of Nanoparticles

In the field of material chemistry, nanoparticles play a vital and indispensable role in modern scientific research and technological applications. They are widely used in the control of microorganisms such as bacteria and fungi. Biosynthetic methods for nanoparticle production can be chemical, physical, or biological. Based on the site of nanostructure formation, several microorganisms demonstrate the ability to reduce and accumulate metals. For example, Pseudomonas stutzeri, isolated from silver ores, can reduce Ag ions and accumulate silver particles, producing nanoparticles in the range of 16–40 nm with an average diameter of 27 nm. Another example includes magnetotactic bacteria, which are capable of producing magnetite (Fe_3O_4) or greigite (Fe_3S_4) nanoparticles. Silver, known for its broad-spectrum antibacterial properties, is able to kill around 650 types of pathogenic microbes. In addition to this, silver possesses unique electrical, optical, and biological properties, making it useful for drug delivery, imaging, catalysis, biosensing, and even wound healing (Soleimani et al., 2021). Biosynthesized metals such as silver, gold, copper, and zinc are effective against both Gram-positive and Gram-negative bacteria, including Bacillus subtilis, Escherichia coli, and Staphylococcus aureus. Among them, silver nanoparticles have received particular attention, especially through green synthesis using plants, bacteria, fungi, and yeasts (Bajpai et al., 2007). For instance, the green synthesis of AgNPs from Streptomyces endophytes has shown significant antimicrobial activity against four plant pathogenic fungi, namely Alternaria, Streptomyces, Pythium, and Aspergillus niger. Similarly, chamomile flowers have been used to synthesize MgO and MnO_2 nanoparticles with promising bioactivities. Furthermore, green-synthesized ZnO and TiO_2 nanoparticles prepared using lemon fruit extract demonstrated strong antibacterial activity against Dickeya dadantii at room temperature, which is a destructive pathogen causing stem and root rot in sweet potato (Maheswari et al., 2012). These examples highlight the potential of eco-friendly synthesis methods, where plant- and microbe-derived nanoparticles can be tailored for specific applications in medicine, agriculture, food preservation, and environmental remediation. Such approaches not only reduce toxicity but also provide scalable and sustainable pathways for future nanotechnology applications Table 1.

Table 1: Comparative overview nanoparticles synthesis Methods

Method	Source	Key mechanism	Advantages	Limitations	References
Chemical	Metal salts+reducing agents	Reduction by chemical reagents	Rapid, controllable	Toxic chemicals, environment hazards	(Yin et al., 2003, Zhang et al., 2006)
Biological (plant)	Plant extracts	Reduction by phytochemicals	Eco-friendly, scalable	Variation in phytochemicals content	(Zare et al., 2013, Lu et al., 2007)
Biological (Microbs)	Bacteria, algae, fungi	Enzymes-mediated reduction	High stability	Slow growth, contamination risk	(Mohammadi et al., 2019, Bajpai et al., 2007)

Different Plants-Mediated Synthesis of Nanoparticles

In green nanotechnology, plant extracts are increasingly employed as natural reducing agents, offering significant advantages over other biological processes because they eliminate the need for complex cell culture and maintenance steps. Plant-mediated nanoparticle synthesis is cost-effective, eco-friendly, and considered safe for humans. Different sizes and shapes of silver, gold, platinum, and titanium nanoparticles can be synthesized from diverse plant parts, including fruits, bark, pericarp, roots, and leaves (Thakka et al., 2010). The general process of synthesis involves collecting the required plant parts, washing them thoroughly with distilled water to remove epiphytes and necrotic material, and then drying and storing the clean plant source in the dark for 10–15 days. The dried samples are pulverized using a household mixer, and about 10 g of powdered material is boiled with 100 ml of deionized distilled water. The resulting solution is then filtered carefully until no insoluble material remains in the broth. The filtrate is subsequently mixed with $AgNO_3$ solution at a final concentration of 1 mM

(Hasan 2015). After mixing, the solution may be oscillated in a shaking incubator, and a distinct color change appears due to the reduction of silver ions to Ag^0. Regular monitoring of the sample through UV–visible spectroscopy is essential to confirm the characteristic absorption peaks of nanoparticles, which indicate successful formation (Saxena et al., 2010). Green nanoparticles have been successfully synthesized from a variety of plant species. For example, root extract of Morinda citrifolia, inflorescence extract of Phoenix dactylifera and Mangifera, Aloe vera extract, latex of Jatropha gossypifolia, fruit extract of Phyllanthus emblica, and aqueous rosemary extract have all been reported to produce nanoparticles with significant biological properties. In particular, rosemary-mediated synthesis has been shown to produce Mg-flower-shaped nanoparticles with strong antibacterial potential (Mirzaei and Darroudi 2017). The quality, stability, size, and morphology of these green-synthesized nanoparticles depend on several critical factors such as the concentration and chemical composition of the plant extract, the concentration of the metal salt precursor, the pH of the reaction medium, and the reaction temperature. Even slight variations in these parameters can significantly alter the yield and functional efficiency of the nanoparticles. For instance, titanium dioxide nanoparticles synthesized from fresh lemon fruit extract demonstrated notable antibacterial activity within just 8 minutes of reaction time. Similarly, Ocimum sanctum (holy basil) leaf extract has been reported to reduce silver ions into nanosilver particles ranging from 4–30 nm in size, which exhibit potent antibacterial activity (Parveen et al., 2016) Table 2.

Table 2: Plant species use in green synthesis of nanoparticles

Plant source	Metal/Nanoparticles	Partical size (nm)	Morphology	Application	References
Aloe vera	Ag	20-50	Spherical	Antibacterial	(Gericke and Pinches 2006)
Ocimum sanctum	Ag	4-30	Irregular	Antimicrobial	(Parveen et al., 2016)
Phyllanthus emblica	Au	15-40	Spherical	Antioxidant	(Mirzaei and Darroudi, 2017)
Lemon fruit extract	TiO_2	10-60	Flower-like	Antibacterial	(Saxena et al., 2010)

Application

Agricultural Applications of Nanoparticles

In modern agriculture, the extensive use of chemicals such as pesticides, fungicides, and herbicides to control pests and diseases has become common practice. However, this approach has led to several harmful consequences, including antagonistic effects on human health, adverse impacts on pollinating insects and livestock, and the contamination of soil and water, which ultimately disrupts ecosystems. To overcome these challenges, nano-scale materials and technologies are being considered as promising alternatives (Pandit et al., 2022). By producing pesticides, fertilizers, and growth regulators through nanoparticles and nanocapsules, it is possible to minimize environmental pollution while enhancing efficiency. Nanomaterials such as polymers, iron oxide nanoparticles, gold nanoparticles, and silver nanoparticles can be synthesized and effectively used as carriers for pesticides, herbicides, and even therapeutic drugs. These carriers improve pharmacokinetic behavior, allowing controlled and sustained release, thereby reducing the frequency of application and lowering toxicity risks. Conventional pesticides, when applied after disease occurrence, often lead to crop losses and residual toxicity in the environment. In contrast, nano enabled formulations can act as both preventive and therapeutic tools, ensuring higher precision and reduced side effects (Hussain et al., 2016). Another emerging approach is disease detection at the molecular level. Identifying biomarkers linked to DNA replication or early viral protein synthesis offers a way to detect and manage infections before visible symptoms appear. This biomarker based strategy, combined with nano-enabled sensors, forms the foundation of smart agriculture systems. Moreover, nano-based diagnostic kits can significantly improve both the speed and accuracy of detection, enabling early intervention (Figure 2). Additionally, integrating nanosensors into soil and water monitoring can provide real-time data on nutrient availability, pathogen presence, and environmental stress, further supporting sustainable farming practices. Table 3.

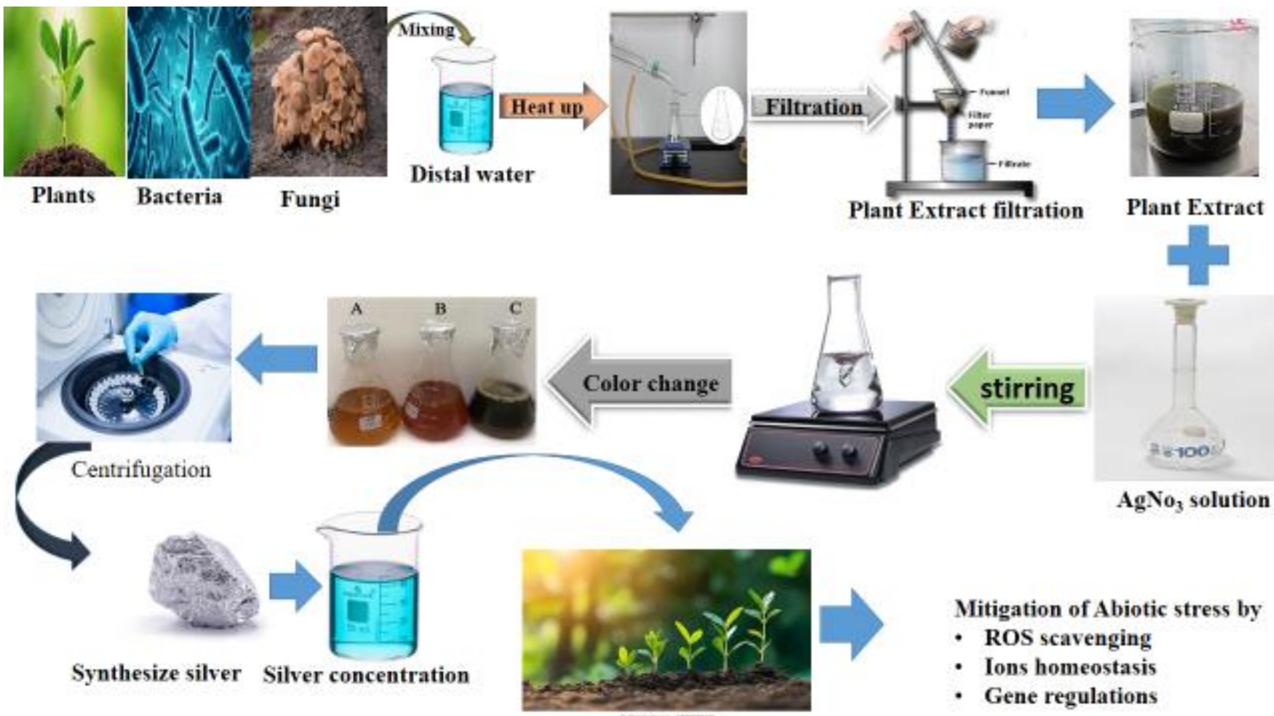

Figure 2. Abiotic stress mitigation

Table 3: Role of Biogenic Nanoparticles in Abiotic Stress Mitigation

Stress type	Nanoparticles	Mechanism	Physiological effects	References
Salinity	Si-NPs	Na^+ exclusion, ROS scavenging	Improved chlorophyll, osmotic balance	(Rizwan et al., 2019)
Acidity	ZnO-NPs	Competition with Al^{3+} ions	Reduced root stunting, enhanced P uptake	(Adrees et al., 2020)
Drought	TiO_2-NPs	Enhanced antioxidant enzymes	Higher RWC and proline	(Khan et al., 2020)
Heavy metal	Fe_2O_3-NPs	Chelation and detoxification	Reduced metal uptake	(Masood et al., 2021)

Nanotechnology in Food Safety and Packaging

Oxygen tends to act as one of the key factors in the food industry that can cause food spoilage and discoloration. One of the main implementations of Nanotechnology within the food industry is the creation of fresh plastics for food packaging. These Nanoparticles in return are processed to produce plastics that are used for packaging of foods. In the new plastic, the Nanoparticles are known to be spiked, acting as a barricade used for blockage in order to prevent oxygen diffusion. Other than that, the pathway for the oxygen to enter the package should be long, the result of that is, and the food deterioration is imminent in the future. According to "Predicala 2009", Nano-coatings are produced to prevent fruits from weight loss and shrinkage, thus covering them completely (Pantidos and Horsfall 2014). It has been the goal of many production companies to develop smart packaging to optimize the shelf life of the product. A packaging system developed with such technology will be in itself enough to repair minor gaps within packaging, as well as responding to environmental conditions when climate change occurs and alert the customers regarding the contamination of food. None other than Nanotechnology can provide the solutions for these problems. Here are some of the examples: the changing of permeability of foils, enhancing the properties of the barrier (mechanical, thermal, chemical and microbiological), ameliorate the mechanical and heat resistance of the packaging, evolving the already developed active antimicrobial and antifungal surfaces with sensing and protection. The top example regarding the production of Nanotechnology is the Ethylene absorbent (Sharma et al., 2019). Ethylene, a gas that is produced by fruits in order to increase the probability of food decay, is absorbed by the Nanomaterials in the absorbent ethylene, thus increasing the tenacity of fruits for an extended period. In order to monitor the agricultural products, Nano barcodes and Nano processing can also be used as a measure. According to "Prasanna, 2007" As new discoveries are made in the world of Nanotechnology, in the same manner that normal barcodes operate, Nano-based barcodes can also perform the similar function like helping to track the food products and keeping a check on the quality of food products, thus producing an entire record in a matter of minutes, or less. The biosensor is another example of the advanced Nano-technology, that comprises of a biological element, that is the same as a cell, an enzyme or an antibody, linked to a small transducer, a device powered by one system that in return supplies the same power to a different system in another form, a form that is required by that other system. Biosensors detect and record every change occurring in every cell and molecule that is used to measure, identify and test the test substance, even at the lowest concentrations of the substance about to be tested. When a substance hitches to a biological component, the transducer then produces a signal that is proportional to the number of components. In case of a high concentration of bacteria in a certain food product, the biosensor will perform the duty of producing a strong signal that would indicate that the food is not sanitary and hence, not safe to be consumed. With a technology so sharp and so cutting edge, it is easy to check the amount of food for their safety in consumption (Rane et al., 2018).

Nanotechnology in Pest and Disease Management

At present, one of the most widely adopted and economical strategies to manage pests and plant diseases is the use of synthetic chemicals such as pesticides, fungicides, and herbicides. However, the increasing reliance on these inputs, along with the high cost of biological control methods, has resulted in serious drawbacks. Overuse and abandoned application of pesticides have caused multiple harms, including adverse impacts on human health, pollinators, livestock, and contamination of soil and water, leading to direct and indirect damage to ecosystems. To address these issues, the application of nano-scale materials has emerged as a promising solution. Unlike conventional chemicals, nano-formulated pesticides and fertilizers can act in a targeted manner, delivering active ingredients precisely to the infected or vulnerable plant tissues. Such smart nano-scale carriers often exhibit self-regulating functions, ensuring that only the required amount of drug is released at the right site, thereby reducing waste and toxicity. Nanotechnology in agriculture also contributes to environmental protection by enabling controlled or delayed release through nanoparticles and nanocapsules. These formulations not only improve efficiency but also reduce the frequency of applications. A wide variety of nanomaterials, including polymer nanoparticles, iron oxide nanoparticles, silver nanoparticles, and gold nanoparticles, can be synthesized and functionalized to serve as carriers for pesticides, growth regulators, or therapeutic agents. Their pharmacokinetic behavior is influenced by size, shape, and surface modifications, which in turn control drug release kinetics. This results in sustained delivery of active molecules and minimizes crop losses caused by untimely application (Rane et al., 2018). One of the greatest challenges in plant protection remains viral infections, as they are difficult to control once established. Therefore, early detection is critical. Advances in nano-enabled diagnostics, particularly virus detection kits, have enabled rapid identification of specific virus strains and the stage of infection. Biomarker-based detection, such as monitoring viral DNA replication or early viral protein synthesis, allows timely intervention. Furthermore, nanosensors can detect differential protein expression in healthy versus infected plants, providing insights into infection cycles and improving disease management (Tsekhmistrenko et al., 2020). Looking ahead, nano-based tools and "smart" agricultural systems hold great promise. The integration of nanosensors for soil health monitoring, nutrient availability tracking, and real-time pathogen detection could revolutionize precision farming (Reverberi et al., 2017). Such approaches will not only enhance crop protection but also promote sustainable and eco-friendly agricultural practices.

Mitigation of nanoparticles

Nanoparticle-Mediated Salinity Stress Alleviation

The application of nanoparticles to mitigate salinity stress involves a methodology designed to counteract both osmotic and ionic stress in plants. The process typically employs green-synthesized nanoparticles such as silicon (Si-NPs), zinc oxide (ZnO-NPs), and selenium (Se-NPs) due to their roles in enhancing plant defense mechanisms. The standard approach involves applying a specific concentration of NPs, often between 50-100 mg/L, through seed priming or foliar spray (Rizwan et al., 2019). The primary mechanism is the reduction of sodium (Na^+) ion uptake and translocation. For instance, Si-NPs facilitate the deposition of silica in root endodermal cells, creating a physical barrier that limits the apoplastic flow of Na^+ into the stele, thereby maintaining a healthier potassium-to-sodium (K^+/Na^+) ratio (Alsaeedi et al., 2019). Concurrently, NPs enhance the plant's osmotic adjustment by stimulating the production of osmolytes like proline and boost the activity of antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT) to scavenge reactive oxygen species (ROS) (Khan et al., 2020). The effectiveness of this methodology is evaluated by measuring improved germination rates, increased biomass, higher chlorophyll content, and reduced oxidative stress markers like malondialdehyde (MDA) in treated plants under saline conditions.

Nanoparticle-Based Mitigation of Soil Acidity and Metal Toxicity

The amelioration of soil acidity, which leads to aluminum (Al^{3+}) and manganese (Mn^{2+}) toxicity, utilizes a methodology centered on the detoxification of the rhizosphere using nanoparticles. This strategy primarily involves the use of zinc oxide (ZnO-NPs) and iron oxide (Fe_2O_3-NPs) applied as a soil drench or seed coating (Rossi et al., 2017). The key mechanism lies in the interaction between nanoparticles and toxic ions. ZnO-NPs can release Zn^{2+} ions that compete with Al^{3+} for uptake sites on root surfaces, reducing aluminum absorption (Adrees et al., 2020). More significantly, the presence of NPs stimulates root exudation of organic acids, such as citrate and malate. These acids chelate Al^{3+} ions in the soil, forming stable, non-toxic complexes that prevent aluminum from damaging root tips and inhibiting growth (Hussain et al., 2018). This directly alleviates the primary symptom of acidity stress—severe root stunting. Additionally, nanoparticles can improve the availability of essential nutrients like phosphorus, which is often fixed in insoluble forms in acidic soils. The success of this method is assessed by observing significant improvements in root architecture, reduced aluminum concentration in plant tissues, and enhanced nutrient uptake, leading to overall better plant performance in acidic conditions (Masood et al., 2021).

Mitigation of Drought Stress Using Nanoparticles

The application of nanoparticles to ameliorate drought stress involves a methodology aimed at enhancing the plant's water retention capacity, osmotic adjustment, and antioxidant defense system under water-deficient conditions. This approach typically utilizes nanoparticles such as silicon (Si-NPs), zinc oxide (ZnO-NPs), and titanium dioxide (TiO_2-NPs) due to their unique properties in modulating plant physiological responses. The standard methodological practice involves the application of these NPs, often at concentrations ranging from 50 to 100 mg/L, through seed priming or foliar spray before or during the onset of drought stress (Rizwan et al., 2019). The mechanisms are multifaceted: Si-NPs, for instance, contribute to the formation of a silica layer on leaf surfaces, which reduces cuticular transpiration and improves water-use efficiency (Alsaeedi, et al., 2019). Simultaneously, nanoparticles act as nano-elicitors, triggering the biosynthesis of osmoprotectants like proline and soluble sugars, which help maintain cell turgor pressure. Furthermore, NPs enhance the activity of key antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), which effectively scavenge the excess reactive oxygen species (ROS) generated under drought stress, thereby protecting cellular membranes from oxidative damage as indicated by reduced malondialdehyde (MDA) levels (Khan et al., 2020). Studies have also shown that nanoparticles can improve root architecture, enabling deeper soil water exploration. The efficacy of this methodology is evaluated by measuring relative water content, leaf area, biomass accumulation, stomatal conductance, and overall yield under drought conditions compared to untreated stressed plants (Adrees et al., 2020).

Alleviation of Temperature Stress Using Nanoparticles

The mitigation of temperature stress, both high (heat) and low (chill), through nanoparticle application leverages their role in stabilizing cellular membranes, protecting photosynthetic apparatus, and modulating stress-responsive gene expression. The methodology commonly employs nanoparticles like silicon (Si-NPs), selenium (Se-NPs), and zinc oxide (ZnO-NPs). Application is typically performed via foliar spraying or root irrigation with NP solutions at critical growth stages preceding or during stress periods (Rossi et al., 2017). Under heat stress, nanoparticles help in the accumulation of heat shock proteins (HSPs) and osmolytes, which protect enzymatic and structural proteins from denaturation (Iqbal et al., 2021). They also play a crucial role in maintaining the integrity of thylakoid membranes in chloroplasts, thereby preserving photosynthetic efficiency and chlorophyll content. Under cold stress, NPs enhance the fluidity of cell membranes, preventing leakage of ions and metabolites, and boost antioxidant systems to counteract chilling-induced oxidative burst (Masood et al., 2021). For instance, Se-NPs have been reported to increase the unsaturated fatty acid content in membranes, which is vital for maintaining membrane flexibility at low temperatures. The success of this methodological strategy is assessed by evaluating membrane stability index, photosynthetic rate, electrolyte leakage, concentration of stress metabolites, and ultimately, the survival rate and productivity of crops exposed to supra- or sub-optimal temperatures (Hussain et al., 2018).

Recent Advances in Biogenic Nanoparticles for Abiotic Stress Tolerance (2015–2025)

Over the past decade, research on biologically synthesized nanoparticles has expanded rapidly, focusing on their roles in mitigating abiotic stress in plants. Table 4 provides a comprehensive summary of key studies conducted between 2015 and 2025, highlighting various nanoparticle types, biological synthesis sources, target plants, stress conditions, tools and analytical techniques used, and major findings. These studies collectively demonstrate the effectiveness of biogenic nanoparticles especially those synthesized from plant and microbial extracts—in enhancing plant tolerance to drought, salinity, temperature, and heavy metal stress through improved antioxidant regulation, ion homeostasis, and gene modulation. Table 4.

Table 4: Data collection from 2015 to 2025 published papers

Year	Biological source / NP type	Target plant / stress	Tools/ Technics	Major findings	Reference
2015	Aloevera extract/AgNPs	Rice/Salinity	UV–Vis, FTIR, SEM, XRD	Enhanced germination, antioxidant enzymes, improved Na^+/K^+ ratio	Singh et al., 2015
2015	Bacillus-mediated AgNPs Arabidopsis/ Oxidative stress	Arabidopsis/ Oxidative stress	TEM, qPCR, DLS Reduced ROS	induction of stress-responsive genes	Kumar et al., 2015
2016	Azadirachta indica (Neem) extract / ZnO NPs	Wheat/ Drought	UV–Vis, TEM, FTIR	Improved RWC, chlorophyll, osmolyte accumulatin	Li et al., 2016
2016	Fungal-mediated AgNPs	Tomato/ Bacterial disease	SEM, EDX, GC-MS	Strong antimicrobial effect; reduced disease severity	Wang et al., 2022
2017	Ocimum sanctum / TiO_2 NPs	Tomato/Heat	XRD, SEM, chlorophyll fluorescence	Increased photosynthetic rate, higher proline	Van Nguyen., 2022
2017	Streptomyces sp. / AgNPs	Chickpea/ Drought	ICP-MS, qPCR, TEM	Enhanced antioxidant system and drought tolerance	Shang et al., 2019
2018	Moringa oleifera extract / CuO NPs	Tomato/Heat	Heat SEM, XRD, photosynthesis assays	Improved photosynthetic efficiency and antioxidant enzymes	Khan et al., 2018
2018	Green-synthesized Si NPs	Maize/Salinity	UV–Vis, FTIR, ICP-OES	Reduced Na^+ uptake; improved K^+/Na^+ balance	Zhao et al., 2019
2019	Tridax procumbens / Fe_3O_4 NPs	Mustard/ Cadmium	FTIR, XRD, DLS	Decreased Cd uptake; reduced lipid peroxidation	Shang & Singh, 2019

2019	Algae-mediated ZnO NPs	Rice/Drought	SEM, HPLC	enzyme assays Enhanced antioxidant defense and water retention	Zhao et al., 2019
2020	Fungal-mediated AgNPs	Rice/Drought	SEM, EDX, proteomics	Induced stress-responsive proteins; improved water-use efficiency	Elsheery et al., 2010
2020	Moringa-mediated Fe_2O_3 NPs	Mustard/ Aluminum toxicity Soil assays	ICP-OES, root analysis	Reduced Al uptake and root damage; improved root architecture	Hussain et al., 2020
2021	Green-tea extract / TiO_2 NPs	Maize/Salinity	UV–Vis, TEM, qPCR Stabilized chlorophyll	increased osmolytes and ion homeostasis	Ahmad et al., 2021
2021	Camellia sinensis-derived SeNPs	Soybean/ Salinity	DLS, enzyme assays, ICP-MS Enhanced SOD & CAT activities	improved tolerance	Alsaeedi et al., 2021
2021	Endophytic bacteria-mediated AuNPs	Arabidopsis / Heavy metal stress	TEM, RNA-seq, ICP-OES	Downregulated metal transporters; reduced uptake	Gomez et al., 2021
2022	Neem leaf extract / AgNPs	Mungbean/ Salinity	DLS, SEM	growth assays Improved germination and antioxidant enzyme activity	Tripathi et al., 2017
2022	Microalgae-mediated ZnO NPs	Chickpea/ Drought	FTIR, SEM, HPLC	Increased chlorophyll and enzymatic antioxidant defense	Patel et al., 2022
2023	Lemon-peel extract / CuO NPs	Chickpea/ Drought	UV–Vis, TEM	ROS assays Higher biomass and lower ROS accumulation	Masood et al., 2023
2023	Plant-extract SiO_2 NPs	Rice/ Submergence & Salinity	SEM, qPCR	photosynthesis assays Improved submergence recovery, ion homeostasis	Singh & Roy, 2023
2023	Seaweed-mediated AgNPs	Wheat/Salinity	XRD, TEM	enzyme assays Enhanced antioxidant responses and yield parameters	Chen et al., 2023
2024	Endophytic-fungi AuNPs	Rice / Heavy metal detox	TEM, ICP-OES	enzyme assays Lowered	Li et al., 2024

				metal accumulation; increased detox enzymes	
2024	Bamboo-extract SiO_2 NPs	Barley/Drought	UV–Vis, FTIR, qPCR	Upregulation of stress genes; improved RWC and yield	Tripathi, et al., 2017
2024	Streptomyces-mediated Fe_3O_4 NPs	Soybean/ Metal stress	SEM, ICP-MS	proteomics Enhanced metal chelation; reduced shoot accumulation	Van Nguyen & Patel, 2022
2025	Bamboo-based extract / SiO_2 NPs	Rice / Multi-stress	UV–Vis, FTIR, SEM, qPCR	Improved salinity & submergence tolerance; eco-safe routes	Zhang et al., 2025

Research gaps and Future direction

Research Gaps

The research highlights the significant promise of biologically synthesized nanoparticles (NPs) for sustainable agriculture but concurrently underscores critical research gaps that must be addressed to translate this potential into practical reality. The most prominent gap is the insufficient understanding of the mechanistic pathways of NP-plant interaction. While it is known that biogenic NPs enhance antioxidant systems, regulate genes, and improve photosynthesis, the precise molecular-level events—from the initial uptake and translocation pathways within plant tissues to the specific signaling cascades and transcription factors they modulate—remain a "black box." This lack of fundamental knowledge hinders the rational design of NPs for specific physiological outcomes. Closely linked is the gap concerning long-term ecological safety and environmental impact**.** The very properties that make NPs effective also raise questions about their persistence, transformation, and fate in agro-ecosystems. Critical investigations are needed to determine if these particles accumulate in soils, disrupt microbial communities, leach into groundwater, or enter the food chain, posing risks to higher trophic levels. Without comprehensive life-cycle assessments, their widespread application carries potential unforeseen consequences.

Furthermore, a significant translational gap exists between controlled laboratory studies and real-world field application. Most research is confined to greenhouses under idealized conditions, lacking validation against the complex, combined stresses plants face in the field. This gap extends to a lack of optimized, crop-specific and stress-specific protocols. The optimal NP type, size, coating, concentration, and method of application for a given crop (e.g., rice under salinity vs. tomato under drought) are largely undefined, and the line between a beneficial and a phytotoxic dose remains blurred.

Finally, there is a gap in comparative and integrative studies. Systematic research directly comparing the efficacy, cost, and safety of biogenic NPs against conventional agrochemicals and chemically synthesized NPs is scarce. Moreover, their potential synergies within integrated pest and nutrient management systems, combining them with biofertilizers or traditional breeding, are unexplored. Addressing these gaps is paramount for developing biogenic NPs into a safe, effective, and trusted tool for enhancing global food security.

Future plan

Elucidating Molecular Mechanisms and Nano-Bio Interfaces

The foremost plan is to decode the precise molecular dialogues between biogenic nanoparticles (NPs) and plant systems. This requires a shift from phenomenological observation to mechanistic discovery. Future work will employ integrated omics technologies—transcriptomics, proteomics, and metabolomics—to map the global changes in gene expression, protein synthesis, and metabolic pathways induced by NP application. A key objective is to identify the primary receptors and signaling hubs, such as specific mitogen-activated protein kinase (MAPK) cascades or hormone pathways, that NPs activate. Furthermore, advanced imaging and spectroscopic techniques will be used to track NP uptake, internalization, and subcellular localization in real-time, clarifying their journey from application to action.

Comprehensive Environmental Risk Assessment and Lifecycle Analysis

Prior to large-scale adoption, a rigorous and long-term environmental safety profile is essential. Future research must systematically investigate the lifecycle of biogenic NPs in agro-ecosystems. This involves studying their persistence, biodegradation, and potential for transformation in different soil types over multiple cropping seasons. Critical ecotoxicological assessments will focus on their impact on non-target soil organisms, including beneficial microbial communities, mycorrhizal fungi, and earthworms. Studies must also evaluate the potential for trophic transfer and bioaccumulation to ensure food chain safety and inform regulatory frameworks.

Field-Level Validation and Agronomic Optimization

Bridging the lab-to-field gap is a critical milestone. The future plan mandates extensive multi-location field trials under diverse pedoclimatic conditions to validate the efficacy of biogenic NPs against combined abiotic stresses. These trials will be crucial for developing agronomically sound protocols. Concurrently, research must focus on optimizing NP characteristics—such as size, shape, surface charge, and coating—for specific crop-stress combinations. This includes establishing precise dosage windows that maximize benefits while avoiding phytotoxicity and ensuring the economic viability of the technology for end-user farmers.

Development of Integrated and Synergistic Formulations

Finally, to maximize resilience and sustainability, future efforts should explore the integration of biogenic NPs into holistic crop management systems. This involves researching their synergistic effects with other biologicals, such as plant growth-promoting rhizobacteria (PGPR), biopesticides, and organic amendments. The goal is to develop novel, multi-functional formulations that enhance nutrient use efficiency, improve soil health, and provide broad-spectrum stress tolerance, thereby reducing the reliance on conventional agrochemicals and building more robust agricultural systems.

Conclusion

Abiotic stresses remain a major barrier to achieving stable agricultural productivity, especially under changing climatic conditions. Conventional strategies for stress management often fail to provide sustainable solutions due to their limitations in efficiency, cost, and environmental safety. Biologically synthesized nanoparticles (NPs) present a promising alternative, offering eco-friendly, economical, and biocompatible means to mitigate plant stress. Their unique physicochemical properties enable plants to overcome adverse conditions by enhancing antioxidant defense systems, maintaining ion balance, regulating stress-responsive genes, and improving photosynthetic performance. Unlike chemically synthesized nanoparticles, biogenic NPs minimize toxic effects and integrate naturally into plant systems, thereby strengthening stress tolerance without compromising environmental safety. The application of these nanoparticles in agriculture opens new opportunities for developing resilient crop varieties and improving overall yield stability. However, despite their potential, the mechanisms of nanoparticle–plant interactions remain insufficiently understood, and their long-term ecological impacts require further investigation. Future studies should focus on molecular-level interactions, dosage optimization, and field-scale validation to ensure safe and effective use. Overall, biologically synthesized nanoparticles represent a transformative approach in plant stress management and hold significant promise for sustainable agriculture and food security in the face of global environmental challenges.

Declaration

Acknowledgment: The authors would like to acknowledge the support from their respective institutions.
Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.
Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Ethics approval/declaration: N/A
Consent to participate: N/A
Consent for publication: N/A
Data availability: No datasets were generated or analysed during the current study.
Author's contribution: Pukraj Ud Din writing and analyzing the manuscript. All authors contributed to the conceptualization, and review of the manuscript.

References

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 oxide nanoparticles. Chemosphere, 238, 124681.

Ali, S., Mehmood, A. and Khan, N. (2021) Uptake, Translocation, and Consequences of Nanomaterials on Plant Growth and Stress Adaptation. Journal of Nanomaterials, 2021, Article ID: 6677616.

Alsaeedi, A., El-Ramady, H., Alshaal, T., El-Garawany, M., Elhawat, N., & Al-Otaibi, A. (2019). Silica nanoparticles boost growth and productivity of cucumber under drought stress through enhanced hydraulic conductance. Journal of Plant Growth Regulation, 38(2), 321-330.

Bajpai, S.K., Mohan, Y.M., Bajpai, M., Tankhiwale, R. and Thomas, V. (2007) Synthesis of Polymer Stabilized Silver and Gold Nanostructures. Journal of Nanoscience and Nanotechnology, 7, 29943010.

Callegari, A., Tonti, D., Chergui, M. (2003) Photochemically Grown Silver Nanoparticles with Wavelength-Controlled Size and Shape. Nano Letters, 3, 1565-1568.

Dimitrijevic, N.M., Bartels, D.M., Jonah, C.D., Takahashi, K. and Rajh, T. (2001) Radiolytically Induced Formation and Optical Absorption Spectra of Colloidal Silver Nanoparticles in Supercritical Ethane. The Journal of Physical Chemistry B,105, 954-959.

Elmer, W. and White, J.C. (2018) The Future of Nanotechnology in Plant Pathology. Annual Review of Phytopathology, 56, 111-133.

Elsheery, N. I., Sunoj, V. S. J., Wen, Y., Zhu, J. J., Muralidharan, G., & Cao, K. F. (2020). Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photoprotection in sugarcane. Plant Physiology and Biochemistry, 149, 50-60.

Gopinath, V., MubarakAli, D., Priyadarshini, S., Priyadharsshini, N. M., Thajuddin, N., & Velusamy, P. (2012). Biosynthesis of silver nanoparticles from *Tribulus terrestris* and its antimicrobial activity: A novel biological approach. *Colloids and Surfaces, B: Biointerfaces*, *96*, 69–74.

Hasan, S. (2015) A Review on Nanoparticles: Their Synthesis and Types. Research Journal of Recent Sciences, 4, 1-3

Hu, J., Cai, W., Li, Y. and Zeng, H. (2005) Oxygen-Induced Enhancement of Surface Plasmon Resonance of Silver Nanoparticles for Silver-Coated Soda-Lime Glass. Journal of Physics: Condensed Matter, 17, 5349-5354.

Hussain, A., Ali, S., Rizwan, M., Zia-ur-Rehman, M., Javed, M. R., & Imran, M. (2018). Zinc oxide nanoparticles alter the wheat physiological response and reduce the cadmium uptake by plants. Environmental Pollution, 242, 1136-1146.

Hussain, I., Singh, N.B., Singh, A., Singh, H. and Singh, S.C. (2016) Green Synthesis of Nanoparticles and Its Potential Application. Biotechnology Letters, 38, 545-560

Iqbal, Z., Sarkhosh, A., Balal, R. M., Rauf, S., Khan, N., Altaf, M. A., ... & Shahid, M. A. (2021). Silicon nanoparticles mitigate hypoxia-induced oxidative damage by improving antioxidants activities and concentration of osmolyte in Southern Highbush blueberry plants. Agronomy, 11(11), 2143.

Iqbal, Z., Sarkhosh, A., Balal, R.M., Rauf, S., Khan, N., Altaf, M.A., Camara-Zapata, J.M., Garcia-Sanchez, F. and Shahid, M.A. (2021) Silicon Nanoparticles Mitigate Hypoxia-Induced Oxidative Damage by Improving Antioxidants Activities and Concentration of Osmolytes in Southern Highbush Blueberry Plants. Agronomy, 11, Article No. 2143.

Khan, M. N., AlSolami, M. A., Basahi, R. A., Siddiqui, M. H., Al-Huqail, A. A., Abbas, Z. K., ... & Hu, Y. (2020). Nitric oxide is involved in nano-titanium dioxide-induced activation of antioxidant defense system in fava bean under drought stress. Plant Physiology and Biochemistry, 156, 136-145.

Khan, N. and Bano, A. (2016) Modulation of Phytoremediation and Plant Growth by the Treatment with PGPR, Ag Nanoparticle and Untreated Municipal Wastewater. International Journal of Phytoremediation, 18, 1258-1269.

Khan, N., & Bano, A. (2016). Role of plant growth promoting rhizobacteria and Ag-nano particle in the bioremediation of heavy metals and maize growth under municipal wastewater irrigation. *International Journal of Phytoremediation*, *18*(3), 211–221.

Kim, M.J., McNally, B., Murata, K. and Meller, A. (2007) Characteristics of Solid-State Nanometre Pores Fabricated Using a Transmission Electron Microscope. Nanotechnology, 18, Article ID: 205302.

Li, J., Wu, H., Santana, I., Fahlgren, M., & Giraldo, J. P. (2023). Nanobiotechnology-based strategies for enhanced crop stress resilience. Nature Food, 4(11), 949-966. https://doi.org/10.1038/s43016-023-00873-z

Lu, Y., Spyra, P., Mei, Y., Ballauff, M. and Pich, A. (2007) Composite Hydrogels: Robust Carriers for Catalytic Nanoparticles. Macromolecular Chemistry and Physics, 208, 254-261.

Maheswari, R.U., Prabha, A.L., Nandagopalan, V. and Anburaja, V. (2012) Green Synthesis of Silver Nanoparticles by Using Rhizome Extract of Dioscorea oppositifolia L. and Their Anti Microbial Activity against Human Pathogens. Journal of Pharmaceutical and Biological Sciences, 1, 38-42.

Masood, K., Yasmin, H., Batool, S., Ilyas, N., Nosheen, A., Naz, R., Khan, N., Hassan, M.N., Aldhahrani, A. and Althobaiti, F. (2021) A Strategy for Mitigating Avian Colibacillosis Disease Using Plant Growth Promoting Rhizobacteria and Green Synthesized Zinc Oxide Nanoparticles. Saudi Journal of Biological Sciences, 28, 4957-4968.

Masood, K., Yasmin, H., Batool, S., Ilyas, N., Nosheen, A., Naz, R., ... & Althobaiti, F. (2021). A strategy for mitigating avian colibacillosis disease using plant growth promoting rhizobacteria and green synthesized zinc oxide nanoparticles. Saudi Journal of Biological Sciences, 28, 4957-4968.

Mirzaei, H. and Darroudi, M. (2017) Zinc Oxide Nanoparticles: Biological Synthesis and Biomedical Applications. Ceramics International, 43, 907-914.

Mohammadi, F., Yousefi, M. and Ghahremanzadeh, R. (2019) Green Synthesis, Characterization and Antimicrobial Activity of Silver Nanoparticles (AgNPs) Using Leaves and Stems Extract of Some Plants. Advanced Journal of Chemistry-Section A (Theoretical, Engineering and Applied Chemistry), 2, 266-275.

Mohammadlou, M., Maghsoudi, H. and Jafarizadeh-Malmiri, H. (2016) A Review on Green Silver Nanoparticles Based on Plants: Synthesis, Potential Applications and Eco-Friendly Approach. International Food Research Journal, 232, 446-463

Mubraiz, N., Bano, A., Mahmood, T. and Khan, N. (2021) Microbial and Plant Assisted Synthesis of Cobalt Oxide Nanoparticles and Their Antimicrobial Activities. Agronomy, 11, Article No. 1607.

Mujeebur, R.K. and Tanveer, F.R. (2014) Nanotechnology: Scope and Application in Plant Disease Management. Plant Pathology Journal, 13, 214-231.

Naik, R.R., Stringer, S.J., Agarwal, G., Jones, S.E. and Stone, M.O. (2002) Biomimetic Synthesis and Patterning of Silver Nanoparticles. Nature Materials, 1, 169-172.

Narayanan, K.B. and Sakthivel, N. (2010) Biological Synthesis of Metal Nanoparticles by Microbes. Advances in Colloid and Interface Science, 156, 1-13.

Natarajan, K., Selvaraj, S., & Ramachandra, M. V. (2010). Microbial production of silver nanoparticles. *Digest Journal of Nanomaterials and Biostructures*, *5*(1), 135–140.

Noor, R., Yasmin, H., Ilyas, N., Nosheen, A., Hassan, M.N., Mumtaz, S., Khan, N., Ahmad, A. and Ahmad, P. (2022) Comparative Analysis of Iron Oxide Nanoparticles Synthesized from Ginger (Zingiber officinale) and Cumin Seeds (Cuminum cyminum) to Induce Resistance in Wheat against Drought Stress. Chemosphere, 292, Article ID: 133201.

Pandit, C., Roy, A., Ghotekar, S., Khusro, A., Islam, M.N., Emran, T.B., Lam, S.E., Khandaker, M.U. and Bradley, D.A. (2022) Biological Agents for Synthesis of Nanoparticles and Their Applications. Journal of King Saud University-Science, 34, Article ID: 101869.

Pantidos, N. and Horsfall, L.E. (2014) Biological Synthesis of Metallic Nanoparticles by Bacteria, Fungi and Plants. Journal of Nanomedicine & Nanotechnology, 5, Article No. 233.

Parveen, K., Banse, V. and Ledwani, L. (2016) Green Synthesis of Nanoparticles: Their Advantages and Disadvantages. AIP Conference Proceedings, 1724, Article ID: 020048.

Rane, A.V., Kanny, K., Abitha, V.K. and Thomas, S. (2018) Methods for Synthesis of Nanoparticles and Fabrication of Nanocomposites. In: Bhagyaraj, S.M., Oluwafemi, O.S., et al., Eds., Synthesis of Inorganic Nanomaterials, Woodhead Publishing, Sawston, 121-139. Reverberi, A., Vocciante, M., Lunghi, E., Pietrelli, L. and Fabiano, B. (2017) New Trends in the Synthesis of Nanoparticles by Green Methods. Chemical Engineering Transactions, 61, 667-672

Rizwan, M., Ali, S., Ali, B., Adrees, M., Arshad, M., Hussain, A., ... & Ibrahim, M. (2019). Alleviation of drought stress in maize by selenium nanoparticles. Chemosphere, 235, 844-855.

Rossi, L., Zhang, W., & Ma, X. (2017). Cerium oxide nanoparticles improve heat stress tolerance in tomato plants. Plant Physiology and Biochemistry, 119, 102-111.

Sastry, M., Ahmad, A., Islam, N.I. and Kumar, R. (2003) Biosynthesis of Metal Nanoparticles Using Fungi and Actinomycetes. Current Science, 85, 162-170.

Sattar, S., Siddiqui, S., Shahzad, A., Bano, A., Naeem, M., Hussain, R., Khan, N., Jan, B.L. and Yasmin, H. (2022) Comparative Analysis of Microbial Consortiums and Nanoparticles for Rehabilitating Petroleum Waste Contaminated Soils. Molecules, 27, Article No. 1945.

Saxena, A., Tripathi, R.M. and Singh, R.P. (2010) Biological Synthesis of Silver Nanoparticles by Using Onion (Allium cepa) Extract and Their Antibacterial Activity. Digest Journal of Nanomaterials and Biostructures, 5, 427-432

Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., Yin, H., & Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection: a review. Molecules, 24(14), 2558. https://doi.org/10.3390/molecules24142558

Sharma, D., Kanchi, S. and Bisetty, K. (2019) Biogenic Synthesis of Nanoparticles: A Review. Arabian Journal of chemistry, 12, 3576-3600.

Soleimani, M. and Habibi-Pirkoohi, M. (2017) Biosynthesis of Silver Nanoparticles Using Chlorella Vulgaris and Evaluation of the Antibacterial Efficacy against Staphylococcus aureus. Avicenna Journal of Medical Biotechnology, 9, 120-12

Soleimani, M. F., Almutairi, K. F., Alotaibi, M., Shami, A., Alhammad, B. A., & Battaglia, M. L. (2017). Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use? Plants, 10(1), 2.

Sun, Y., Yin, Y., Mayers, B.T., Herricks, T. and Xia, Y. (2002) Uniform form Silver Nanowires Synthesis by Reducing AgNO3 with Ethylene Glycol in Presence of Seeds and Poly (Vinyl Pyrrolidone). Chemistry of Materials, 14, 4736-4745.

Swami, A., Selvakannan, P.R., Pasricha, R. and Sastry, M. (2004) One-Step Synthesis of Ordered Two Dimensional Assemblies of Silver Nanoparticles by the Spontaneous Reduction of Silver Ions by Pentadecylphenol Langmuir Monolayers. The Journal of Physical Chemistry B, 108, 19269-19275.

Thakkar, K.N., Mhatre, S.S. and Parikh, R.Y. (2010) Biological Synthesis of Metallic Nanoparticles. Nanomedicine: Nanotechnology, Biology and Medicine, 6, 257-262.

Tripathi, D. K., Singh, S., Singh, V. P., Prasad, S. M., Dubey, N. K., & Chauhan, D. K. (2017). Silicon nanoparticles more effectively alleviated UV-B stress than silicon in wheat (Triticum aestivum) seedlings. Plant Physiology and Biochemistry, 110, 70-81.

Tsekhmistrenko, S.I., Bityutskyy, V.S., Tsekhmistrenko, O.S., Horalskyi, L.P., Tymoshok, N.O. and Spivak, M.Y. (2020) Bacterial Synthesis of Nanoparticles: A Green Approach. Biosystems Diversity, 28, 9-17.

Van Nguyen, D., Nguyen, H. M., Le, N. T., Nguyen, K. H., Nguyen, H. T., Le, H. M., ... & Tran, L. S. P. (2022). Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. Journal of Plant Growth Regulation, 41(1), 364-375.

Wang, Y., Wang, L., Ma, C., Wang, K., & Hao, Y. (2021). Effects of cerium oxide nanoparticles on the growth and photosynthetic characteristics of tomato seedlings under cadmium stress. Environmental Science and Pollution Research, 28(11), 14123-14133.

Worrall, E.A., Hamid, A., Mody, K.T., Mitter, N. and Pappu, H.R. (2018) Nanotechnology for Plant Disease Management. Agronomy, 8, Article No. 285.

Yin, B., Ma, H., Wang, S. and Chen, S. (2003) Electrochemical Synthesis of Silver Nanoparticles under Protection of Poly (N-Vinylpyrrolidone). The Journal of Physical Chemistry B, 107, 8898-8904.

Zare, B., Babaie, S., Setayesh, N. and Shahverdi, A.R. (2013) Isolation and Characterization of a Fungus for Extracellular Synthesis of Small Selenium Nanoparticles. Nanomedicine Journal, 1, 13-19.

Zhang, L., Shen, Y., Xie, A., Li, S., Jin, B. and Zhang, Q. (2006) One-Step Synthesis of Monodisperse Silver Nanoparticles Beneath Vitamin E Langmuir Monolayers. The Journal of Physical Chemistry B, 110, 6615-6620.