Pak. J. Bot., 57(6): 2197-2220, 2025. DOI: http://dx.doi.org/10.30848/PJB2025-6(5)

HARNESSING GREEN NANOTECHNOLOGY: EXPLORING THE POTENTIAL OF SILVER, COPPER, AND THEIR NANOCOMPOSITES FOR BIOMEDICAL AND AGRICULTURAL APPLICATIONS

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Abstract

This review highlights the potential of green nanotechnology, focusing on silver, copper, and silver-copper bimetallic nanoparticles (NPs) due to their unique physicochemical properties, dual biomedical and agricultural applications, and established efficacy compared to other nanoparticles. Silver NPs, renowned for their remarkable antimicrobial, antioxidant, and anticancer properties, are among the most widely studied due to their versatility and effectiveness in addressing multidrug-resistant pathogens, agricultural pests, and catalytic efficiency in biochemical reactions. Copper NPs were selected for their superior performance in agriculture, demonstrating the ability to mitigate heavy metal toxicity, enhance plant growth through improved photosynthesis and nutrient uptake, and contribute to biomedicine via enzyme inhibition and cytotoxic effects. Silver-copper bimetallic NPs synergize the properties of both metals, offering enhanced catalytic activity, antimicrobial efficacy, oxidative stress mitigation, and DNA damage capabilities, surpassing the performance of single-metal NPs in several applications. Despite their promise, challenges remain, including synthesis inconsistencies, scalability issues, and ecological toxicity. Future research should focus on integrating nanotechnology with advanced techniques such as artificial intelligence and precision agriculture to enhance targeted applications, optimize synthesis, and minimize environmental risks. Addressing these challenges will unlock the full potential of silver, copper, and silver-copper bimetallic NPs, contributing to sustainable agriculture, advancing biomedicine, and supporting global ecological preservation efforts.

Key words: Plant-mediated nanoparticles, Biomedical applications, Sustainable agriculture, Heavy metal toxicity.

Introduction

Since the beginning of the twenty first century nanotechnology enabled synthesis of novel materials for biotechnological, medical and environmental applications. At nanoscale, the materials show uniquefeatures which open new avenues of applications in medicine, agriculture and environment (Bayda *et al*., 2019; Puri *et al*., 2024). Nanoparticles (NPs), because of their small size and large surface area, can lead to improved solubility and highly acceptable bioavailability to pierce through the biological hurdles including brain and pulmonary barriers (Scioli Montoto *et al*., 2020; Almas *et al*., 2024). Among all these emerging technologies, the biogenic synthesis of nanoparticles using plant extracts has been identified as an environment-friendly approach. They provide a green synthesis route using natural phytochemicals and non-toxic reducing agents, which are inexpensive, large scale and do not require the use of toxic chemicals and high temperature and pressure conditions (Gour & Jain, 2019; Shah *et al*., 2024). In biogenic nanoparticle synthesis, biomolecules derived from plants include alkaloids, phenolics, and terpenoids that play a reducing and stabilizing role during synthesis (Ali & Baghdadi, 2024; Roy *et al*., 2025). Besides, this method does not use toxic reagents; it also makes it easy to regulate the size and shapes of the particles, making them even more useful in medicine and diagnostics (Devi *et al*., 2024). For example, phytonanoparticles (PNPs) have specificity to act at the site of action for drug delivery in cancer treatment without triggering the immune system (Tang *et al*., 2021; Jadhav *et al*., 2024). Moreover, the fact that plants can reduce metal ions and remove heavy metal ions from their bodies suggests their possibility to synthesize various metal nanoparticles such as Ag, Se, Fe and Au and metal oxides including ZnO and TiO_2 (Mourdikoudis *et al*., 2018). These advances in green nanotechnology present promising prospects for designing and creating novel drug delivery systems and green materials, promoting biogenic solutions to current issues worldwide (Nasrollahzadeh *et al*., 2019; Akram *et al*., 2023).

Nanoparticles (NPs) have gained profound attention in research and industry segments because of their impressive catalytic properties and various applications, such as energy, biology, and environmental technology (Alshammari *et al*., 2023). Of all types of nanomaterials, CuNPs are the most focused on for many reasons including abundance and pocket-friendly in comparison to other nanomaterials, and versatile in the preparation of new systems (Crisan *et al*., 2021). Copper's redox potential and tunable surface reactivity, as well as its ability to be in more than two oxidation states, also signal it as a very useful property in meta catalysis (Camats *et al*., 2021). This placed copper at a high risk of oxidation, however, progress in stabilizing techniques has made the element strong

(Zhao *et al*., 2023). Especially, copper NPs were found to be very efficient in cross-coupling reactions, thus presenting an environmentally friendly, economic, and which is known for its high toxicity and cost (Che *et al*., 2024). The fact that copper can change its structure and form active catalytic sites indicates the metal's potential for the formation of sustainable and efficient catalytic systems for various industries (Abiso *et al*., 2024). Application of copper nanoparticles proved to be useful in reducing both biotic and abiotic stresses in agriculture (Kaleem *et al*., 2024). They displayed resilience against biotic stress and effective fight against microbes that could harm the crops including bacteria, fungi and viruses (Su *et al*., 2024). For abiotic stress, Copper nanoparticles improved plant resilience to conditions such as water scarcity and salt concentrations and stressed metal toxicities through up-regulating antioxidant enzymes and nutrient assimilation promoting health and productivity (Liu *et al*., 2024). Silver nanoparticles (AgNPs) are admired well-known NPs because of their distinguished characteristic, and they have applications in both the medical and agricultural sectors (Almatroudi, 2024). In biomedical field, AgNPs provide powerful antibacterial activity against bacteria, virus and fungi and are employed in the preparation of the wound dressings, medical device coatings and cancer treatments (Albao *et al*., 2024; Ren *et al*., 2024). This further cement the fact that their applications are not limited to drug delivery, but they can also extend their delivery systems. In Agriculture, the silver nanoparticles contribute to plant diseases control, limited use of pesticide in farming, boosting seed germination, root development and nutrient assimilation (Ahmad *et al*., 2024; Francis *et al*., 2024). Such multipurpose applications make silver nanoparticles appropriate mechanisms for enhancing healthcare and sustainability in agricultural practices. It is possible to produce Ag-Cu NPs by both top-down and bottom-up methods, with their distinctive characteristics. Using chemically selective dealloying and pulsed laser ablation (PLAL), pure and reactive stimuli responsive nanoparticles with great stability and surface characteristics are obtained (Liu *et al*., 2017). Chemical reduction and biosynthesis methods for the formation of NPs allow for size control and environmentally friendly fabrication employing bioactive reagents, for example, plant extracts (Hamouda *et al*., 2023). Such and similar strategies demonstrate that Ag-Cu NPs have prospects in catalysis, antimicrobial purposes, and green nanotechnology.

Bimetallic nanoparticles (BNPs) possess interesting physiochemical characteristics and optical, catalytic, and antibacterial properties.(Malik *et al*., 2023). Of them, Ag-Cu NPs have increased therapeutic antibacterial activity, better stability, and low genotoxicity and so can be optimized as efficient 'green' antibacterial agents (Khan *et al*., 2025; Długosz *et al*., 2021; Manikandan *et al*., 2023). In the process of time, nanotechnology proved to be a more sustainable tool in agriculture and the usage of multi metallic nanoparticles received increased credits due to higher efficiency shown by them in increasing plant growth and stress tolerance than the mono metallic nanoparticles (Dey *et al*., 2024). Investigations on the effects of silver-copper bimetallic nanoparticles on *Eruca sativa* indicated the ability of nanoparticles in acting as nano-fertilizers to improve nutrient uptake efficiency though the practical use has not been well developed (Zaka and Abbasi, 2017). In this review, the importance of green nanotechnology is highlighted across the globe challenges by concentrating on the green synthesis methods such as medicinal plants extract for fabrication of nanoparticles. The biomedical applications of green synthesized silver (Ag), copper (Cu) and Ag-Cu bimetallic nanoparticles (NPs) and agriculture stress busters are described as the significant uses of the nanoparticles for health control and crop improvement. The present review discusses the properties of various metal NPs and their applications: antioxidants, antimicrobial, anticancer, anti-inflammatory cytotoxicity, and catalytic efficiency; it also focuses on limitations such as the lack of scalability and safety threats posed by such NPs. These nanoparticles help solve problems of global health and advancements in agriculture, combining two aspects in a comprehensive approach of the goals of sustainable development.

Review methodology: A comprehensive literature review was conducted to explore the potential of green-synthesized silver (Ag), copper (Cu), and silver-copper bimetallic nanoparticles (Ag-Cu NPs) for biomedical and agricultural applications. Databases such as PubMed, Scopus, Web of Science, Science Direct, and Google Scholar were used to ensure extensive coverage of relevant studies. The review focused on publications from 2011 to 2025, incorporating recent advancements and aligning them with the latest research trends.

The search strategy employed a combination of keywords and Boolean operators to refine the results, ensuring the inclusion of high-quality and relevant literature. Keywords such as "green synthesis, silver nanoparticles, copper nanoparticles, bimetallic nanoparticles, biomedical applications, sustainable agriculture, and nanotechnology" were used in various combinations. Specific terms like antimicrobial, antioxidant, anticancer, plant growth, heavy metal toxicity and catalysis were included to capture studies relevant to the dual applications of these nanoparticles.

The inclusion criteria were:
1. Studies focusing on the green synthesis of Ag, Cu, and Ag-Cu NPs using plant extracts or other eco-friendly methods.
2. Articles describing the biomedical and agricultural applications of these nanoparticles.
3. Peer-reviewed studies providing experimental or preclinical data.
4. Studies published in English.

The exclusion criteria were:
1. Studies focusing solely on chemically synthesized nanoparticles without comparison to green-synthesized NPs.
2. Non-peer-reviewed articles, conference abstracts, and book chapters.
3. Studies published in languages other than English.
4. Duplicate studies or studies with incomplete data.

Nanotechnology: A sustainable approach: Nanotechnology was defined in 1974 by Norio Taniguchi and subsequently revolutionized scientific development through the ability to control material at nanoscale (1 to 100nm) order for various uses (Sun & Gupta, 2020). The field provided new opportunities in areas like biotechnology, nanomedicine and agriculture, being able to answer to global needs like food supply, sustainability, and effective healthcare (Wu *et al.*, 2022). Though, earlier methods for the synthesis of nanoparticles via physical and chemical methods, were characterized by high energy consumption, high cost and ecological impact owing to the use of strong reducing agents (Pal *et al.*, 2019; Nasar *et al.*, 2022). Biological methods mainly plant base pathways evolved as favorable technique, provided environment friendly and economic approach to synthesize nanoparticles exempt from pathogenic points of view related to microbial synthesis (Pal *et al.*, 2019; Alam *et al.*, 2021; Bibi *et al.*, 2023). This approach took advantages of the reducing and stabilizing effect of plant biomolecules, which can be considered as a remarkable progress toward green nanotechnology methods (Kim *et al.*, 2019; Anas *et al.*, 2024; Barbinta-Patrascu *et al.*, 2024). Biomolecules derived from plant extracts, microorganisms, or other biological sources play a crucial role in green synthesis by acting as reducing, capping, and stabilizing agents during nanoparticle formation. These biomolecules, including flavonoids, polyphenols, terpenoids, alkaloids, proteins, and enzymes, reduce metal ions into their metallic or lower oxidation states through electron donation from functional groups such as hydroxyl (-OH), carbonyl (C=O), and amine ($-NH_2$) groups (Shahid *et al.*, 2024; Duraisamy *et al.*, 2025). For example, polyphenols in plant extracts reduce silver ions (Ag^+) to metallic silver (Ag^0), while enzymes in microbial extracts facilitate the reduction of copper ions (Cu^{2+}) to Cu^0 or CuO NPs. Simultaneously, these biomolecules stabilize the nanoparticles by capping their surfaces, preventing aggregation, and influencing their size and shape (Jabeen *et al.*, 2025; Torres-López *et al.*, 2025). Proteins and polysaccharides often act as steric stabilizers, while certain biomolecules like terpenoids perform dual functions of reduction and capping (Abadi *et al.*, 2023). Additionally, biomolecules guide nanoparticle morphology by directing growth along specific crystallographic planes, tailoring their functionality. In bimetallic NPs, such as silver-copper, biomolecules enable the simultaneous reduction of both metal ions, forming synergistic structures with enhanced properties (Sharma *et al.*, 2024). This eco-friendly process not only eliminates the need for toxic chemicals but also enhances nanoparticle stability and functionality, making green synthesis a sustainable alternative for various applications.

The applications of nanotechnology in agriculture and health sectors were the way in which the technology demonstrated its impacts. In agricultural applications, nano-sensors, nano delivery systems and nano fertilizers promoted crop vigor and health, control of pests and diseases, and optimum and even efficient use of fertilizers with less pollution (Sundararajan *et al.*, 2024). Nanotechnology has impacted drugs and drug delivery system, diagnostics, and regenerative medicine in healthcare via using instruments such as liposomes, DNA nanotechnology, and nanofluidic devices (Salvador-Morales & Grodzinski, 2022; Ejidike *et al.*, 2024). However, such issues as the cost of production, toxicity, and effect on the environment continued to be major issues despite the enormous potential of this concept (Shah *et al.*, 2024). This will reduce environmental impacts through green synthesis and spur interdisciplinary efforts to fully deliver on nanotechnology's promise of sustainable development and global impacts. These efforts will not only contribute to raising awareness concerning nanotechnology as a cutting-edge science discipline but also reveal its contribution towards the achievement of sustainable development goals-environmental protection and enhancement of health and agricultural production performance.

Plant-mediated nanoparticles: An eco-friendly approach: Green synthesis using plant materials, received a lot of attention due to the merits associated with plant-mediated synthesis as compared to other methods such as physical and chemical because plant-mediated methods utilize less energy and chemicals than conventional methods (Ovais *et al.*, 2022; Pattoo, 2023; Sheikh *et al.*, 2024). These approaches fit the tenets of green chemistry and will help in reducing the effects on the environment and the cost of production. Different plant parts including roots, stems, leaves, flowers or fruits are good sources of phytochemicals which play the role of reducing and capping agents. Besides, it does not require the use of toxic reagents and makes the process simple, economical and reproducible; an aspect that makes it preferable for large-scale synthesis of nanoparticles (Singh *et al.*, 2023; Anas *et al.*, 2024). Active phytochemicals like flavonoids, alkaloids, saponin and terpenoids play a significant role in the process of reduction of metal ions to nanoparticles and stabilization of the formed particles (Gebre, 2023; Younas *et al.*, 2023; Younis *et al.*, 2024). Thus, these bioactive compounds contribute two-fold, enhance the synthesis process and, at the same time, provide the nanoparticles with the desired characteristics like biocompatibility and multi functionality. For example, *Azadirachta indica* (neem) extract is used green synthesis of silver nanoparticles (Chi *et al.*, 2022), while *Moringa oleifera* for copper oxide nanoparticles (Barani *et al.*, 2024) and *Citrus limon peel* extract for lead oxide, zinc oxide, cadmium oxide and copper oxide nano quantum dots (Yousaf *et al.*, 2024). Plant mediated NPs have been reported to have high antibacterial, antioxidant, and anticancer properties making them ideal for biomedical uses (Chi *et al.*, 2022; Barani *et al.*, 2024; Yousaf *et al.*, 2024).

Apart from medicine, plant-mediated nanoparticles can also be effectively used in different environmental sectors. This is evident in applications such as water treatment, removal of pollutants, and the elimination of hazardous metals. For instance, copper oxide nanoparticles incorporated with *Peganum harmala* is employed in the degradation of industrial dyes (Fekri *et al.*, 2022), and titanium dioxide nanoparticles from *Aloe vera* is efficiently used in photocatalytic reactions (Srujana *et al.*, 2022). In agriculture, these nanoparticles function as both nano-fertilizers and pest repellants that boost produce yield and protect plants against disease and other microclimatic changes (Abasi *et al.*, 2024). This diversity and utility in healthcare and agriculture re-emphasize their relevance and use in sustainable development (Ashraf *et al.*, 2021). However, like other nanobiotechnological tools, plant-mediated nanoparticles have issues related to repeatability, efficiency, and environmental effects. The concentration of phytochemicals in the plants and even in the same plant species at different developmental stages influences the reproducibility of nanoparticles (Mittal, 2024; Shiraz *et al*., 2024). However, high production scale calls for an increase in control of factors such as pH, temperature and concentration of precursors. Overcoming these challenges by optimizing characterization methods and harnessing synergies across disciplines shall expand the applicability of plant-mediated NPs making them the basis of green nanotechnology. The green synthesis of NPs incorporates the following twelve principles of green chemistry: Applying green chemistry to inspire synthetic chemistry; minimizing the utilize of hazardous substances; using renewable biomass-derived materials; using energy efficient methods; inorganic, organometallic, or biological catalysts; using safe solvents and away from toxic solvents; designing less hazardous chemical reactions; using a real time pollution prevention; using white lies down waste; in the course This involved the use of non-toxic reducing and stabilizing agents, proper capping agents for the control of size and shape of NPs for particular uses (Dheyab *et al*., 2024). Fig. 1 shows the schematic representation of plant-mediated synthesis of Ag, CuO and Ag-Cu bimetallic NPs using medicinal plant extracts. The process includes the preparation of extracts from roots, stems, and leaves, followed by their reaction with inorganic salts, with the synthesized NPs characterized using UV-Vis spectroscopy, FTIR, XRD, EDX, and zeta potential analysis.

Comparative benefits and risks of plant-mediated nanoparticles (PMNPs) and chemically synthesized nanoparticles: Green synthesis is a cost-effective alternative to conventional methods due to its reliance on renewable resources, lower energy requirements, and reduced use of toxic chemicals. By utilizing plant extracts and agricultural byproducts as raw materials, green synthesis minimizes the costs associated with synthetic precursors and waste management (Hameed *et al*., 2021; Madani *et al*., 2022). Additionally, the ambient temperature and pressure conditions required for green synthesis significantly decrease energy consumption compared to conventional methods that often demand high-energy inputs (Mohamed *et al*., 2023; Idoko *et al*., 2024). The bioactive compounds in plant extracts serve as both reducing and stabilizing agents, eliminating the need for additional chemical additives or purification steps, thereby further reducing operational costs (Mohamed *et al*., 2023; Mohamed *et al*., 2024). These advantages make green synthesis a scalable and economically viable approach for industrial applications, promoting sustainability and minimizing environmental impact.

Plant-mediated nanoparticles (PMNPs) formulations offer numerous advantages. These nanoparticles possess a high surface area-to-volume ratio, significantly enhancing their functionality. PMNPs improve the solubility and bioavailability of active compounds, facilitating better therapeutic efficacy and ensuring efficient uptake by the reticuloendothelial system (RES), which enhances their distribution within biological systems. Additionally, these formulations improve permeability, absorption, and retention effects, ensuring precise delivery to target sites while minimizing adverse side effects by preventing interactions with normal cells. Moreover, PMNPs offer improved physicochemical stability for therapeutic agents, protecting them from degradation *In vivo* and presenting a safer alternative for biomedical applications (Patil & Chandrasekaran, 2020; Mohamed *et al*., 2024).

In contrast, chemically synthesized nanoparticles, such as silver (Ag), copper (Cu), and silver-copper bimetallic nanoparticles, pose significant risks in agricultural applications. Studies demonstrate their cytotoxic effects on plant growth and physiology. For instance, chemically synthesized silver nanoparticles inhibited seed germination, shoot growth, and root elongation in six plant species, including wheat and lettuce, with severe reductions in germination percentage and seedling vigor index in tomato varieties (Karami Mehrian *et al*., 2016). Chemically synthesized silver nanoparticles also caused damage to chloroplasts, reduced chlorophyll levels in *Vicia faba* seedlings, and triggered oxidative stress (Abdel-Aziz and Rizwan, 2019). Similarly, chemically synthesized copper nanoparticles and silver-copper bimetallic nanoparticles exhibit toxic effects, including reduced shoot elongation, stunted growth, and chlorosis in plants such as *Coriandrum sativum* and *Arabidopsis thaliana* due to oxidative stress and nutrient imbalances (Zuverza-Mena *et al*., 2015; Mottaleb *et al*., 2021). Moreover, copper nanoparticles applied to crops like *Glycine max* and *Allium cepa* resulted in significant tissue damage and reduced seed germination rates (Tortella *et al*., 2024). Ag-Cu bimetallic nanoparticles were shown to disrupt photosynthesis and soil microbial communities, generating excessive reactive oxygen species (ROS), which harmed nutrient cycling and ecosystem health (Hao *et al*., 2024).

These findings underscore the importance of adopting plant-mediated nanoparticles as a safer alternative to chemically synthesized nanoparticles. PMNPs leverage bioactive phytochemical coatings that mitigate harmful interactions, reduce toxicity, and offer environmental and agricultural safety. Future research should focus on optimizing PMNP synthesis to achieve scalability and precise application, balancing agricultural benefits with environmental preservation.

Biomedical applications of plant-mediated nanoparticles (PMNPs): Herbal medicines have long been used to manage various conditions and are now recognized as effective therapeutic agents. Plant-mediated nanoparticles enhance treatment through their nanoscale size, lower drug concentration, rapid drug release, increased bioavailability, and ability to cross the blood-brain barrier. Due to their biocompatibility, PMNPs have demonstrated significant pharmacological potential in biomedicine, including anticancer, antimicrobial, anti-inflammatory, antidiabetic, antioxidant, enzyme inhibitory activity, drug delivery, and cytotoxicity applications. Plant-mediated nanoparticles synthesized by different techniques have been extensively studied for their in-vivo and in-vitro applications (Huang *et al*., 2015; Barathi *et al*., 2024). (Fig. 2 and Table 1) shows the biomedical applications of nanoparticles, emphasizing their multifunctional roles such as antimicrobial, anti-inflammatory, antidiabetic, anticancer, drug delivery, cytotoxicity, antioxidant, and enzyme inhibitory activities, showcasing their potential in therapeutic and diagnostic advancements. Nanoparticles exhibit diverse mechanisms of action in biomedical applications, driven by their unique size, surface properties, and interactions with biological systems at the molecular level. One key mechanism is the generation of reactive oxygen species (ROS), where NPs such as silver and copper disrupt the electron transport chain, leading to oxidative stress and subsequent damage to cellular components, including lipids, proteins, and DNA. For example, silver nanoparticles generate superoxide radicals (O_2^-) and hydroxyl radicals (OH) that disrupt bacterial membranes, while copper nanoparticles catalyze Fenton-like reactions, enhancing ROS production and inducing cytotoxicity in cancer cells (Alfei *et al*., 2024; Farrokhnia *et al*., 2025). NPs also interact with biomolecules, such as proteins and nucleic acids, altering their structure and function. Silver nanoparticles bind to thiol groups in proteins, leading to enzyme inactivation, while copper ions disrupt DNA replication by interacting with phosphate backbones (Lei *et al*., 2024; Malček Šimunková *et al*., 2024). These interactions are particularly valuable in targeted drug delivery, where functionalized NPs bind to specific receptors and precisely deliver therapeutic agents to diseased cells. Once internalized via endocytosis, NPs accumulate in cellular organelles such as lysosomes or mitochondria, triggering intracellular pathways like apoptosis, autophagy, or necrosis, depending on the NP type and dose (Zhang *et al*., 2024). Functionalized NPs also facilitate controlled drug release, triggered by external stimuli such as pH or temperature, enhancing therapeutic efficacy while minimizing side effects. Furthermore, NPs can modulate immune responses, either enhancing them, as seen in their use as vaccine adjuvants, or suppressing inflammation, such as silver nanoparticles inhibiting pro-inflammatory cytokine production (Sun & Yu, 2024). Collectively, these mechanisms underscore the transformative potential of NPs in biomedical applications, while emphasizing the importance of careful design to ensure their efficacy and safety.

Anticancer activity of PMNPs and their mechanisms of action: Plant-mediated nanoparticles have demonstrated significant potential in cancer treatment due to their unique mechanisms of action. These nanoparticles are synthesized using plant extracts such as *Ocimum sanctum*, *Aerva lanata*, *Catharanthus roseus*, *Taxus baccata*, *Artemisia annua*, *Citrus sinensis*, and *Citrus limon*, utilize bioactive compounds like alkaloids, flavonoids, vinblastine, vincristine, taxol, artemisinin, and diosmin to enhance their therapeutic properties. Their anticancer mechanisms primarily involve inducing oxidative stress, causing DNA damage, and triggering mitochondrial dysfunction in cancer cells, ultimately leading to apoptosis and necrosis.(Efferth *et al*., 2015; Ashokkumar *et al*., 2024; Dubey *et al*., 2024; Rahman *et al*., 2024). Silver and copper nanoparticles synthesized through plant-mediated methods have shown remarkable cytotoxicity against various cancer cell lines. For instance, Cu NPs synthesized using *Impatiens chinensis* and *Moringa peregrina* exhibited selective cytotoxicity and targeted breast cancer cells through oxidative stress mediated by ROS, membrane destabilization, and anticancer cell proliferation (Barani *et al*., 2024; Kirubakaran *et al*., 2024). Likewise, bimetallic silver-copper nanocomposites have been shown to exhibit an effective synergistic anticancer behavior by integrating the characteristics of both metals leading to the improved DNA fragmentation and apoptosis routes (Sayed *et al*., 2024; Thirumoorthy *et al*., 2024). Plant mediated nanoparticles also benefits include biocompatibility, precise delivery of the drug to the target site, and much less side effects than normal chemotherapy. Since they can penetrate body tissues which include the blood brain barrier and tend to accumulate themselves in tumor tissues, they make it very useful in treating resistant cancers. These nanoparticles are opening the way towards effectively green and low-cost therapies against cancer, based on natural resources for mass production (Ullah *et al*., 2020; Elnasr *et al*., 2024; Nor *et al*., 2024).

Antimicrobial activity of PMNPs and their mechanisms of action: Nanoparticles derived from plant mediated synthesis using natural plant extracts have exhibited high levels of antimicrobial activity against broad spectrums such as bacteria, fungi and viruses. These nanoparticles utilize bioactive phytochemicals from plant sources like *Ocimum sanctum* (Holy Basil), *Aerva lanata*, *Catharanthus roseus* (Madagascar Periwinkle), and *Artemisia annua* (Sweet Wormwood) to boost on their antimicrobial properties. This paper focuses on AgNPs and CuNPs, as these possess the most remarkable bactericidal and fungicidal properties. The main targets of antimicrobial action include ROS formation, microbial cell membrane disruption, modification of microbial protein and enzyme functions and actions, and microbial DNA injury, leading to death of the pathogen (Ingle *et al*., 2014; Nisar *et al*., 2019; Kanniah *et al*., 2020; Hernández - Díaz *et al*., 2021; Ashokkumar *et al*., 2024). CuNPs derived from plants such as *Moringa stenopetala* and *Salvinia cucullata* possess potent antimicrobial properties, which mainly entail the production of ROS that interfere with the cohesion of microbial cell walls and membranes respectively. These nanoparticles have expressed potential against MDR bacteria, which offers a potential solution to the fight against antibiotic resistance. The ability of CuNPs to adhere to microbial interfaces solely activates oxidative stress, direct damage to the microbe's lipids, and DNA modifications, giving the CuNPs efficiency in combating bacterial and fungal infections (Alavi & Moradi, 2022; Santhosh *et al*., 2023; Tefera & Zeleke, 2024). Nanomaterials like Ag-Cu NPs fabricated using *Vitex negundo*, *Lawsonia inermis*, and *Kigelia pinnata* leaves extract, have improved antimicrobial properties due to synergetic effect. These NPs are developed by linking the ROS generation feature of AgNPs and membrane disruption of CuNPs, giving a dual attacking mechanism against the pathogens. Particularly, such nanoparticles can degrade biofilms and prevent microbes' adhesion on the medical device, which can significantly decrease the risks linked with implant-associated infections. It is noteworthy that the targeted green synthesis of these NPs reduces the adverse environmental and toxicological effects typically related to conventional approaches (Mamatha *et al*., 2021; Gautam *et al*., 2024; Ragavendran *et al*., 2024).

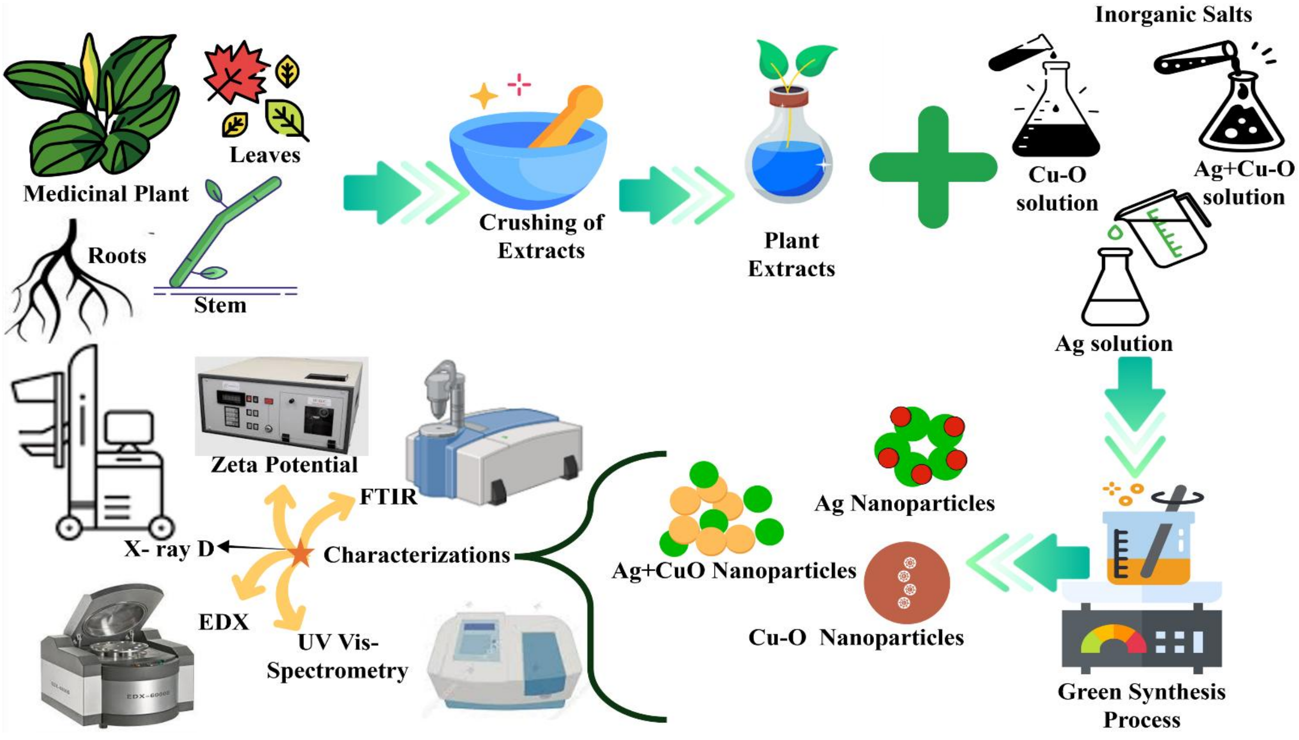

Fig. 1. Schematic representation of the plant-mediated nanoparticles synthesis using medicinal plant extracts. The process involves the preparation of plant extracts from roots, stems, and leaves, followed by their reaction with inorganic salts (Ag and CuO solutions) to synthesize silver (Ag) and copper oxide (CuO) nanoparticles. The synthesized NPs are characterized using various analytical techniques, including UV-Vis spectroscopy, FTIR, X-ray diffraction (XRD), energy-dispersive X-ray spectroscopy (EDX), and zeta potential analysis.

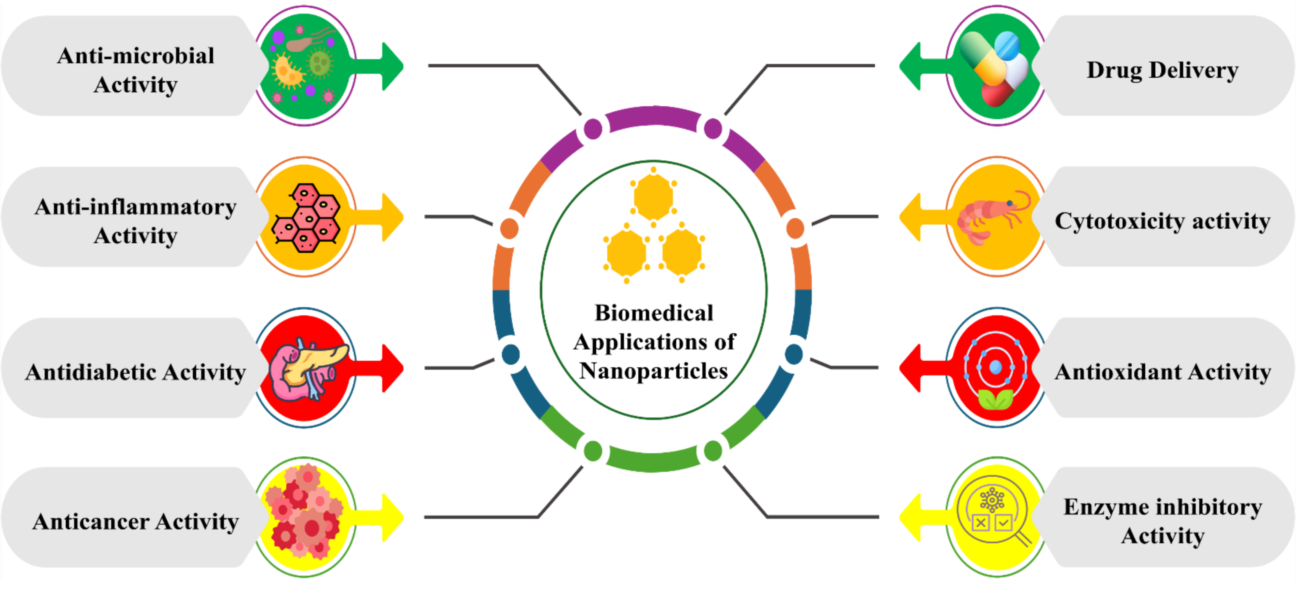

Fig. 2. Biomedical applications of NPs showcasing their multifunctional roles, including anti-microbial, anti-inflammatory, antidiabetic, anticancer, drug delivery, cytotoxicity, antioxidant, and enzyme inhibitory activities. These diverse activities highlight the potential of nanoparticles in advancing therapeutic and diagnostic approaches in healthcare.

Anti-inflammatory activity of PMNPs and their mechanisms of action: Nanoparticles through plant-mediated mechanisms have been seen to exhibit great potentials of combating inflammation through natural bioactive compounds. For instance, copper oxide nanoparticles prepared from aqueous extract of *Camellia sinensis* and *Citrus sinensis* exhibited drugs like anti-inflammatory effects due to the suppression of albumin denaturation and decrease in pro-inflammatory cytokines. These nanoparticles intervene in these inflammatory processes, decrease ROS formation, and inhibit key inflammatory mediators; hence, it may be useful in managing inflammation-related diseases (Singh *et al*., 2023; Bhardwaj *et al*., 2024). Compared to this, AgNPs isolated from *Phragmanthera austroarabica*, *Solanum lycopersicum* and *Astragalus tribuloides* reported anti-inflammatory activity by inhibiting macrophage activity and regulating cytokines. These nanoparticles also suppressed the expression of inflammatory genes that are involved in conditions such as arthritis and psoriasis. The mechanisms include the nanoparticles' cell membrane permeability that further leads to a reduction of the pro-inflammatory factors accompanied by the dual antioxidant and anti-inflammatory effects (Sharifi-Rad *et al*., 2020; Khodeer *et al*., 2023; Mekky *et al*., 2024). Nanoparticles of silver and copper incorporated bimetallic composites are synthesized by *Solanum Lycopersicum*, *Trigonella Foenum Graecum*, and *Vossia Cuspidat* plant extracts created to amplify the anti-inflammatory factors of both the metals. These composites work by employing both the antioxidant properties and the functional effects on inflammatory cells responsible for higher efficacy in inflammation modulation. Such progresses show that plant mediated NPs could be used as safe and cheaper substitutes to traditional inflammatory drugs with minimized side effects and improved biocompatibility (Abd El-Aziz & Farahat, 2023; Azmat & Zafar, 2023).

Antidiabetic, antioxidant, enzyme inhibitory activity of PMNPs and their mechanisms of action: Green synthesis of silver nanoparticles using plants has revealed high biomedical prospects particularly in antidiabetic and antioxidant activities. For instance, the green synthesized AgNPs from *Ocimum sanctum* as well as *Syzygium caryophyllatum* (L.) have highly effective inhibition on α-amylase and α-glucosidase, insulin-responsive enzymes essential for managing blood glucose levels. Furthermore, these NPs protect against oxidative stress through increased antioxidant enzymes activity and neutralization of free radicals. The specificity of the biomolecular pathways involved in diabetes and reduced toxicity makes AgNPs a potential therapeutic tool for treatment of diabetes and oxidative stress (Mishra *et al*., 2023; Bhavi *et al*., 2024). Copper NPs that are widely recognized for enzyme inhibitory and antioxidant activities are coming into focus specifically for the therapeutic potential. CuNPs prepared from the extracts of *Parkia timoriana* and *Mentha spicata* showed pronounced antidiabetic efficacy mainly attributed to a marked inhibition of enzymes such as α-glucosidase which plays a crucial role in carbohydrate metabolism. Moreover, their antioxidant properties evidenced from free radical elimination and decrease in oxidative stress provide shield against cellular devise damage. Due to its biocompatibility and affordability, copper is used as one of the most important components when creating effective plant-based therapeutic agents (Papitha *et al*., 2024; Shahzad *et al*., 2024). Bimetallic Ag/Cu nanoparticles exhibit different characteristics of silver and copper with each element showing improvement in its properties due to the synergistic effect between the two metals, making it suitable in biological applications. Made from plants like *Mentha spicata*, *Argyreia nervosa* and *Syzygium caryophyllatum*, these nanocomposites have better antidiabetic effects due to better enzyme inhibition and metabolic control. Also, they show high antioxidant activity due to synergistic effects of silver and copper ions which can counteract all types of oxidative stress. The combined use of metal ions enhances their therapeutic applications, especially in managing chronic diseases such as diabetes, and oxidative stress (de Carvalho Bernardo *et al*., 2021; Velidandi *et al*., 2023; Kalakonda *et al*., 2024; Shahzad *et al*., 2024).

Drug delivery, and cytotoxic activity of PMNPs and their mechanisms of action: Nanoparticles such as silver and copper and their composites have proven to be effective in drug delivery and cytotoxic effects using the bioactive compounds derived from plant extracts. For example, the drug delivery properties of *Ocimum americanum*-based silver-copper nanocomposites were impressive, increasing the rate of bioavailability and reaching the target tumor cells effectively. These composites take advantage of the enhanced interaction between the constituents to enhance the therapeutic potential of the drugs, especially those related to cancer (Renu *et al*., 2020; Manikandan *et al*., 2023). *Hordeum vulgare* mediated synthesis of AgNPs also showed the dose dependent cytotoxic effects on A549 human lung cancer cells. Due to their character such as small diameter and high surface area they facilitate accurate drug delivery and limited side effects. Similarly, copper nanoparticles isolated from *Adiantum venustum* fronds were investigated for their potent anti-biofilm properties and accumulation capability in biofilm-infected tumor tissues. These nanoparticles help in the controlled release of the drugs and sparing toxicity hazardous to the normal cells; such biocompatible properties make them perfect candidate for clinical uses (Chowdhury *et al*., 2024; Kimta *et al*., 2024). Faceted bimetallic silver-copper nanoparticles within *Aerva lanata* extract have been reported for their application in cytotoxic activities and drug delivery mechanisms. These sorts of nanocomposites utilize their physicochemical characteristics to transport and release drugs at the desired location, for instance biofilm-related tumors as well as intensify the toxicity towards pathogenic cells. Such versatility makes them to enhance the potential of delivering therapeutic and diagnostic functions making them suitable for use in theragnostic which deals with the marriage of diagnostics and therapy for tailored medicine (Thirumoorthy *et al*., 2024; Abbasgholinejad *et al*., 2025). Focusing on the plant-derived NPs, it can be stated that this concept is environmentally friendly and highly effective for modern pharmaceutics. Biocompatibility, green synthesis, and tunable properties open up diverse applications for these NPs to overcome multifaceted biomedical issues such as targeted drug delivery and reduction in the generation of side effects (Vincent *et al*., 2022; Bhardwaj *et al*., 2024). Fig. 3 shows the comprehensive mechanisms and applications of plant mediated NPs, including drug delivery, antimicrobial action, cancer treatment through apoptosis, and antidiabetic effects by enhancing insulin secretion and glucose metabolism.

Heavy Metal Stress: A Global Agricultural Concern: Heavy metal (HM) pollution is one of the major environmental concerns because these pollutants are non-biodegradable, hence exist in the soil for long due to their ability to escape the physical and biological processes of degradation. Their long stay affects soil health, viability of microbes and crop yields while HM's integrate into food chain, leading to bioaccumulation and adverse human health effects including neurotoxicity, osteoporosis, infertility and death (Huang *et al*., 2019; Mitra *et al*., 2022; Khan *et al*., 2023). The most dangerous HMs include

Arsenic (As), Cadmium (Cd), Lead (Pb) and Mercury (Hg) and according to WHO standards the tolerance level for the concentration of Soil HMs is 0.2mg/k for Arsenic, 0.05mg/k for Cadmium, 0.1mg/k for Lead & 0.5mg/k for Mercury (Substances and Registry, 2017). Some of the sources of HM contamination include urbanization, industrialization, the use of agrochemicals, mining, and poor management of wastes and disposal, such pollutants are reported to affect more than 50% of the polluted sites worldwide (Khalid *et al*., 2017; Zhou *et al*., 2020). Immediate agricultural and physiological approaches are required to address HM stress and improve structure of soils. Special attention was given to the heavy metals and metalloids, which are chromium (Cr), lead (Pb), arsenic (As), cadmium (Cd), mercury (Hg) and nickel (Ni), and all these are considered as environmental threats and the main dangers for food security. The increasing exposure to heavy metals in the past has led to emergent concerns regarding the sustainability of human life as wells as agricultural crops (Anas *et al*., 2024; Devi, 2024). Heavy metals contamination in agricultural soils of the region were found to have potential risks on the fertility and productivity of the plants and safety of human beings. Chromium, arsenic, cadmium and lead triggered loss of cellular functions, and slowed plant metabolism and growth. These contaminants changed the characteristics of the soil by decreasing crops productivity and making humans get in touch with severe diseases from foods that were infected by these contaminants. The bioavailability in the plants and the soil foreign properties determined toxicity levels of the highly poisonous agricultural chemicals (Angon *et al*., 2024). Pollutants such as Cr, Cd, Pb, Hg, As, and Ni have affected crop quality and yield to various degrees (Rai *et al*., 2019). These metals interfere with the normal functioning of the plant by hinder photosynthesis, nutrient absorption and thus the growth of the plant (Angon *et al*., 2024). Different crops like rice, wheat, maize, and medicinal plants are more sensitive having the propensity to absorb heavy metals in their biomass (Khan *et al*., 2023; Bouzidi & Krouma, 2024). This contamination changes the physical and chemical characteristics of the soil and affects the cell organelles of plants causing oxidative stress which reduces crop productivity (Chau *et al*., 2024). The experience shows that the consumption of toxic crops threatens human health and is becoming a pressing need for the development of prevention measures to protect people and the globe (Li & Imran, 2024).

Agricultural Applications: Plant-mediated silver, copper, and Ag-Cu bimetallic NPs are eco-friendly tools in agriculture. Synthesized using plant extracts, these NPs enhance seed germination, root and shoot growth, and nutrient uptake. They protect crops from pathogens, boost chlorophyll content and photosynthetic efficiency, and improve antioxidant activity, ultimately increasing crop yields and promoting sustainable farming practices as shown in (Fig. 4 & Table 2).

Role of PMNPs for heavy metal stress mitigation: The use of nanotechnology holds good potential in managing HM toxicity in agricultural systems, through the manipulated crop productivity and soil improvement by nanoparticles (NPs). These NPs, well below 100 nm in size, have desired features that make them useful as soil conditioners, growth promoters, nano-fertilizers, and nano-pesticides, which enhances smart farming (Ahmed *et al*., 2022; Faizan *et al*., 2023; Saleem *et al*., 2024). Furthermore, NPs reduce abiotic stress by increasing stress-tolerance genes and proteins also reduces the accumulation of toxic HM and aid in detoxification of persistent toxic pollutants and increases the resistance to the HM toxicity and risks (Haris *et al*., 2023). NP-based analysis of foliar treatment has been found to have superior repair impacts than the general methodology (Singh *et al*., 2021). But still, systematic investigations on the mechanisms involved in NPs-HM interactions, the effects of environmental factors, and toxicity are scarce, as a proof of future work required to guarantee the safe and efficient utilization of NPs in agriculture (Akhtar *et al*., 2022; Sharma *et al*., 2022). Seed priming is a soil treatment where seeds are treated with certain chemicals before sowing in delicate environments with an aim of improving crop performance (Marthandan *et al*., 2020). Some of the widely applied techniques are hydropriming, hormonal priming, osmo-priming, and biopriming (Nile *et al*., 2022). Nanopriming, a new method, utilizes NPs as seed priming input, enhancing seed viability and tolerance to biotic stresses such as salinity and drought. This method stimulates nanopore formation on seed coats enhancing water uptake and releasing reactive oxygen species which are crucial for seed dormancy and germination (Rai-Kalal *et al*., 2021; Silva *et al*., 2022).

Impact of green synthesis approach in improving crop quality and productivity: Novel approach in using the green synthesis of metal-based NPs has greatly enhanced the quality and yield of crops with minimal impacts on the environment. Compared to chemically synthesized NPs, organisms involved in green synthesis incorporate plant extracts, microorganisms, or agricultural waste, making it environmentally friendly and has a low toxicity coefficient, thus increasing biocompatibility (Jiang *et al*., 2022; Sundararajan *et al*., 2024). NPs synthesized from green method include gold, silver, and silica, which were confirmed to increase seed germination rate, nutrient uptake, stress tolerance, and thus increase crop yield and quality (Acharya *et al*., 2019; Alabdallah & Hasan, 2021). For instance, plant mediated synthesized silver NPs evidenced an enhanced vigor and tolerance against abiotic stress in crops like onions and wheat as well as, enhance the soil health for better plant growth under drought stress; silica NPs (Snehal and Lohani, 2018; Singh *et al*., 2023). The process of using green-synthesized NPs involves their structure which makes nutrient delivery and stress reduction enhanced. These NPs induce ROS, upregulate antioxidant enzyme activity, and promote photosynthetic efficiency in plants under stress (Dikshit *et al*., 2021; Toksha *et al*., 2021). In addition, the green synthesis enables the use of the plant in reducing the reliance on chemical fertilizers and pesticides, safer agriculture (Bahrulolum *et al*., 2021; Rabalao *et al*., 2022; Munir *et al*., 2024). The most recent sustainable development of green NPs offers a possible solution to the challenges facing crop production as well as environmental conservation.

Table 1. Biomedical applications of plant-mediated nanoparticles.

Plant species	Examples of nanoparticles	Characteristics of nanoparticles (Morphology and Size)	Applications	Role of nanoparticles	References
Peganum harmala (Harmala/Africa rue)	Ag NPs	Spherical, 12.6 to 35.7nm	Antimicrobial activity	Antibacterial against *Escherichia coli* and *Staphylococcus aureus,* Antifungal *Candida albicans*	(Ullah *et al*., 2024)
Azadirachta indica (Neem)	CuO NPs Ag NPs	Crystalline, 25.26nm Spherical, 10 to 100nm	Antimicrobial biomedical activity	Antibacterial activity against pathogens *Escherichia coli* and *Staphylococcus aureus,* Drug delivery and diagnostic imaging, Act as carriers for targeted therapy	(Ahsan *et al*., 2023; Yadeta Gemachu &Lealem Birhanu, 2024)
Ocimum sanctum (Tulsi/Holy Basil)	Ag NPs Cu NPs	Spherical, 3-55nm Spherical, 75 to 123nm Spherical, 37.61nm	Biomedical antimicrobial activity anticancer properties	Managing diabetic wounds, Antibacterial activity against *Acinetobacter baumannii,* Cancer treatment	(Usha *et al*., 2017; Gautam *et al*., 2023)
Curcuma longa (Turmeric)	Ag-Cu NPs	Crystalline, 20nm Semi-spherical, 60.92nm	Anticancer potential electrocatalytic antimicrobial activity	Valuable in chemical sensing and energy conversion applications, Inhibiting cancer cell proliferation, Antimicrobial action of Ag-Cu nanoparticles is attributed to their ability to generate reactive oxygen species (ROS) upon exposure to bacteria, leading to cellular damage	(Jacob *et al*., 2022; Yan *et al*., 2024)
Moringa oleifera (Drumstick tree)	Ag NPs Cu NPs	Spherical, 50-60nm Spherical, 35.8 to 49.2nm	Antioxidant antimicrobial activity hemolytic	Antibacterial properties against pathogens such as *E. coli* and *Staphylococcus aureus* due to their ability to disrupt bacterial membranes and generate reactive oxygen species, Enhancing therapeutic applications	(Das *et al*., 2020; Mohammed & Hawar, 2022)
Camellia sinensis (Green Tea)	Ag NPs	Spherical, 44nm	Therapeuti antimicrobial activity	Antimicrobial activities, AgNPs activity against *Staphylococcus aureus*	(Khalid Mohamed *et al*., 2021)
Allium sativum (Garlic)	Ag NPs	Spherical, 145.3nm Crystalline, 19.8nm	Antimicrobial activity, Drug delivery	Antibacterial *E. coli*, *Staphylococcus aureus*, and *Candida albicans,* Silver nanoparticles with isoniazid hydrazide have shown potential for targeted tuberculosis treatment	(Mohamed *et al*., 2021; Kebede Urge *et al*., 2023; Ditta *et al*., 2024)
Zingiber officinale (Ginger)	Ag NPs	Spherical, 5 to 35nm	Catalytic activity, Antimicrobial activity	Excellent catalytic degradation capabilities for hazardous dyes such as Direct Orange 26 (DO26) and Direct Blue 15 (DB15), Antibacterial properties against *E. coli* and *Staphylococcus aureus*, CuO NPs also exhibit antimicrobial effects, making them suitable for applications in wound healing and infection control	(Hu *et al*., 2022; Jing *et al*., 2022; Ramzan *et al*., 2022)
Aloe vera (Aloe)	Ag NPs CuO NPs Ag-CuO NPs	Spherical, 20 to 24nm Spherical, 10 to 50nm 20 to 80nm	Wound healing antimicrobial activity environmental applications	Ability to promote healing while preventing infection Exhibit significant antibacterial properties against *Escherichia coli* and *Staphylococcus aureus,* CuO and Ag-CuO nanoparticles contribute to environmental remediation efforts, particularly in wastewater treatment	(Khan *et al*., 2017; Begum *et al*., 2020; Kamala Nalini & Vijayaraghavan, 2020)
Phyllanthus emblica (Amla/Indian Gooseberry)	Ag NPs	Spherical, 25nm Spherical, 10 to 50nm	Environmental applications antioxidant properties	CuO and Ag-CuO nanoparticles contribute to environmental remediation efforts, articularly in wastewater treatment, Have potent antioxidant activity	(Meena *et al*., 2020; Hossain *et al*., 2024; Sharma *et al*., 2024)
Terminalia arjuna (Arjuna)	Ag NPs CuO NPs	Spherical, 10 to 50nm Spherical, 15 to 60nm	Antimicrobial activity catalytic activity	Antibacterial properties against *Staphylococcus aureus* and *Escherichia coli*, Ag NPs have shown excellent catalytic properties for the degradation of dyes such as methyl orange and methylene blue, with degradation efficiencies exceeding 90%	(Sharma & Gupta, 2021; Singh *et al*., 2022; Ramalakshmi *et al*., 2024)
Tinospora cordifolia (Guduchi/Giloy)	Ag NPs	Spherical, 6.32 to 25nm Spherical, 10 to 50nm	Antimicrobial activity therapeutic properties	Antibacterial properties against a broad spectrum of pathogens, including *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa,* Beneficial in reducing oxidative stress in biological systems, Applications for wound healing and infection control	(Prajwala *et al*., 2021; Ghosh *et al*., 2023; Javaid *et al*., 2024)

Table 1. (Cont'd.).

Plant species	Examples of nanoparticles	Characteristics of nanoparticles (Morphology and Size)	Applications	Role of nanoparticles	References
Withania somnifera (Ashwagandha)	Cu NPs Ag NPs	Spherical, 6.28 Spherical, 74 to 88nm	Antioxidant properties drug delivery applications	Targeted therapies due to their enhanced stability and biocompatibility	(Shanmugapriya *et al*., 2022; Jabeen *et al*., 2023; Mengesha *et al*., 2024)
Mentha piperita (Peppermint)	Cu NPs Ag NPs	Spherical, 27.5nm Spherical, 20 to 70nm	Biocontrol antimicrobial activity	Managing fruit rot disease of chilli caused by *Colletotrichum capsica*, Antibacterial properties against *Staphylococcus aureus* and *Escherichia coli*	(Iliger *et al*., 2021; Joshi *et al*., 2024)
Eucalyptus globulus (Eucalyptus)	CuO NPs Cu NPs Ag NPs	Spherical, 67nm Spherical, 10 to 130nm Spherical, 20-30nm	Antioxidant properties dye degradation antimicrobial activity	Silver nanoparticles synthesized from *Eucalyptus* have shown potent antioxidant activity and degrade the dye, Antibacterial properties against pathogens such as *Xanthomonas citri* and *Escherichia coli*	(Atiq *et al*., 2022; Anwaar *et al*., 2024; Salgado *et al*., 2024)
Citrus limon (Lemon)	Ag NPs Ag-Cu NPs Cu NPs	Spherical, 59.74nm Spherical, 50nm Spherical, 75nm	Antioxidant applications antimicrobial agents wound healing	Potentially used in pharmaceuticals in oxidative stress, Antibacterial properties, Promoting wound healing processes	(Khane *et al*., 2022; Malik *et al*., 2023; Shareef *et al*., 2023)
Carica papaya (Papaya)	Ag NPs Cu NPs	Spherical, 50 to 250nm Aggregates/ Irregular 20 to 100nm	Antimicrobial agents photocatalytic applications biomedical applications	Antibacterial activity against *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus subtilis*. Cu NPs synthesized from papaya extracts have been explored for their photocatalytic properties in dye degradation processes, Used in medical devices and wound dressings	(Dulta *et al*., 2018; Jackson *et al*., 2018; Bere *et al*., 2021)
Ficus religiosa (Peepal Tree)	Ag NPs Cu NPs	Spherical, 10 to 100nm Irregular, 20 to 200nm	Antimicrobial agents environmental remediation biomedical applications	Ag NPs antibacterial activity against *E. coli* and *Staphylococcus aureus*, Treating heavy metals in wastewater, achieving removal efficiencies exceeding 74% for chromium contamination, Ability to enhance drug efficacy	(Sankar *et al*., 2014; Riaz *et al*., 2022)
Sida rhombifolia (Arrowleaf sida)	CuO NPs Ag/CuO NPs	Spherical, 40nm Spherical, 65nm	Catalytic	Catalytic hydrogenation & photodegradation of aromatics	(Babu & Antony, 2019)
Zingiber officinale (Ginger)	Ag NPs	Spherical, 15nm	Antimicrobial	Antibacterial activity	(Velmurugan *et al*., 2014)
Tussilago farfara (Coltsfoot)	Ag NPs	Spherical, 13.57nm	Biomedical	Anti-cancerous	(Lee *et al*., 2019)
Polianthus tuberosa (Tuberose)	Ag NPs	Oval, 50nm		Larvicidal activity	(Rawani, 2017)
Cleome viscose (Asian spiderflower)	Ag NPs	Spherical, 20-50nm	Therapeutic antimicrobial	Anticancer activity antibacterial	(Lakshmanan *et al*., 2018)
Syzygium alternifolium (Mogi/Movi)	CuO NPs	Spherical, 2-69nm	Antimicrobial	Antiviral	(Yugandhar *et al*., 2018)
Ficus carica (Common Fig)	Ag NPs	Spherical, 10-30nm	Antioxidant activity	Antioxidant activity	(Kumar *et al*., 2016)
Coffea arabica (Arabian coffee)	Ag NPs	Ellipsoidal, 20-30nm	Antimicrobial	Antibacterial	(Dhand *et al*., 2016)

Table 2. Role of plant-mediated nanoparticles in agriculture.

Plant species	Examples of nanoparticles	Characteristics of nanoparticles (Morphology and Size)	Applications/Role	References
Azadirachta indica (Neem)	Ag NPs, Cu NPs, Ag-Cu NPs	Spherical, 8 to 60nm	Mitigation of heavy metal stress	(Khan & Javed, 2021; Saravanan, 2021)
Allium cepa (Onion)	Cu NPs, Ag NPs	Anisotropic, 100nm Spherical, ≤ 10nm	Drought tolerance and increase yield of wheat	(Ahmed *et al.*, 2021; Ejaz *et al.*, 2023)
Moringa oleifera (Drumstick tree)	Ag NPs	Spherical, 8-28nm	Alleviate biotic stress by improving biochemical and mineral profile	(Ejaz *et al.*, 2023)
Triticum aestivum (Wheat)	Ag NPs	Crystalline, spherical, 87nm	Regulated salt tolerance	(Wahid *et al.*, 2020)
Mangifera indica (Mango)	Ag NPs	Spherical, 39nm	Biocontrol agent for plant pathogen	(Rana *et al.*, 2023)
Ocimum americanum (Hoary Basil)	Ag-CuO NPs	Crystalline, 69.80nm	Reduce marine microalgae growth	(Manikandan *et al.*, 2023)
Sesbania aculeata (Danchi)	CuO NPs	Spherical, 10.1nm	Functioned as a strong antibacterial agent and bio-fertilizer for sustaining crop yield of *Brassica nigra*	(Tamil Elakkiya *et al.*, 2022)
Withania coagulans (Paneer doddi/Ashutosh booti)	Ag NPs	Spherical, 14nm	Improvement of root and shoot length, anthocyanin contents of *Withania coagulans*	(Tripathi *et al.*, 2021)
Crocus sativus (Saffron)	Ag NPs	Crystalline, 70 to 96nm	Recovered flooding stress	(Rezvani *et al.*, 2012)
Adiantum lunulatum (Walking maidenhair fern)	CuO NPs	Quasi-spherical, 1.5-20nm	Enhanced the total phenolic and flavonoid contents and increased activities of *Lens culinaris*	(Sarkar *et al.*, 2020)
Triticum aestivum (Wheat)	Ag NPs	Spherical, 35nm	Significantly alleviated salt stress	(Mohamed *et al.*, 2017)
Brassica campestris (Mustard)	CuO NPs	Rectangular, 56nm	Heavy metal stress of Cd (2 mg/L)	(Alhaithloul *et al.*, 2023)
Capparis spinosa (Caper bush)	Ag NPs	Spherical, 25 nm	Salinity stress up to (25 and 100 mM)	(Abou-Zeid & Ismail, 2018)
Triticum aestivum (Wheat)	Ag NPs	Spherical, 42.1nm	Salinity stress up to (100 mM)	(Wahid *et al.*, 2020)
Moringa oleifera (Drumstick tree)	Ag NPs	Spherical, 60nm	Heat stress improvement (35–40 ◦C; 3 h/day)	(Iqbal *et al.*, 2019)
Hevea barsiliensis (Rubber tree)	Ag NPs Cu NPs	Spherical, 37nm Crystalline, 89nm	Heavy metal stress specifically cadmium 15.0 mg kg−1	(Guidelli *et al.*, 2011; Sebastian *et al.*, 2018; Sebastian *et al.*, 2019; Noppradit *et al.*, 2024)
Cocos nucifera (Coconut tree)	Ag NPs	Spherical, 21nm	Heavy metal stress improvement of cadmium 0.01% w/w	(Sebastian *et al.*, 2018)
Cuminum cyminum (Cumin – Jeera)	Ag NPs	Spherical, hexagonal, roughly circular, 53nm	Improved Salt tolerance	(Ekhtiyari & Moraghebi, 2011)
Lens culinaris Medic (Lentil)	Ag NPs	Spheroidal and spherical, 79nm	Intensified drought stress tolerance	(Hojjat & Hojjat, 2016)
Hordeum vulgare (Barly)	CuO NPs	Round, 83nm	Heavy metal stress specifically Cd (100 mg/L)	(Fu *et al.*, 2022)
Phaseolus vulgaris (bean)	Ag NPs	Prism or spherical, 81nm	Enhanced chilling stress tolerance	(Prażak *et al.*, 2020)
Triticum aestivum (Wheat)	Ag NPs	Spherical, 10 to 30nm	Improvement of plant tolerance against salt stress	(Abou-Zeid & Ismail, 2018)
Solanum lycopersicum (Tomato)	Cu NPs	Spherical, 36nm	Salinity stress	(Pérez-Labrada *et al.*, 2019)
Satureja hortensis	Ag NPs	Spherical, 64nm	Improved salt stress tolerance	(Nejatzadeh, 2021)
Triticum aestivum (Wheat)	CuNPs	Cubical, 43nm	Heavy metal stress specifically Cr (3.5 mg/kg)	(Noman *et al.*, 2020)
Triticum aestivum (Wheat)	Ag NPs	Spherical, 47nm	Increased heat tolerance	(Iqbal *et al.*, 2019)
Zea mays (Maize)	Cu NPs	Rectangular, 18nm	Alleviating drought stress	(Van Nguyen *et al.*, 2022)
Oryza sativa japonia (Rice)	CuO NPs	Sphere-shaped, 45nm	Heavy metal stress specifically As (120 to 140 mg/g)	(Liu *et al.*, 2018)
Arabidopsis thaliana (Thale cress)	CuO NPs	Cubical, 62nm	Salinity stress of 200 mM salt	(Shah *et al.*, 2023)
Laurencia papillosa	Ag NPs	Spherical, 6.9 to 15nm	Cu, Fe, Zn, Mn remediation	(El Shehawy *et al.*, 2023)
Eucalyptus	Ag NPs	Spherical, 20.3nm	Co and Pb removal	(Attatsi & Nsiah, 2020)
Mentha piperita (Peppermint)	CuO NPs	Spherical, 150nm	Pb, Ni and Cd remediation	(Mahmoud *et al.*, 2021)
Syzygium alternifolium	CuO NPs	Spherical, 2 to 69nm	Heavy metal stress	(Yugandhar *et al.*, 2018)
Citrus sinensis (Orange peels)	CuO NPs	Aggregate, 140nm	Pb, Ni and Cd remediation	(Mahmoud *et al.*, 2021)
Guar	CuO NPs	Spherical, 15 to 30nm	Cu heavy metal stress	(Ahmadi-Nouraldinvand *et al.*, 2022)
Zingiber officinale (Ginger)	Ag NPs, CuO NPs	Rod, 8.6nm	Cd and Pb removal	(Verma & Bharadvaja, 2022)

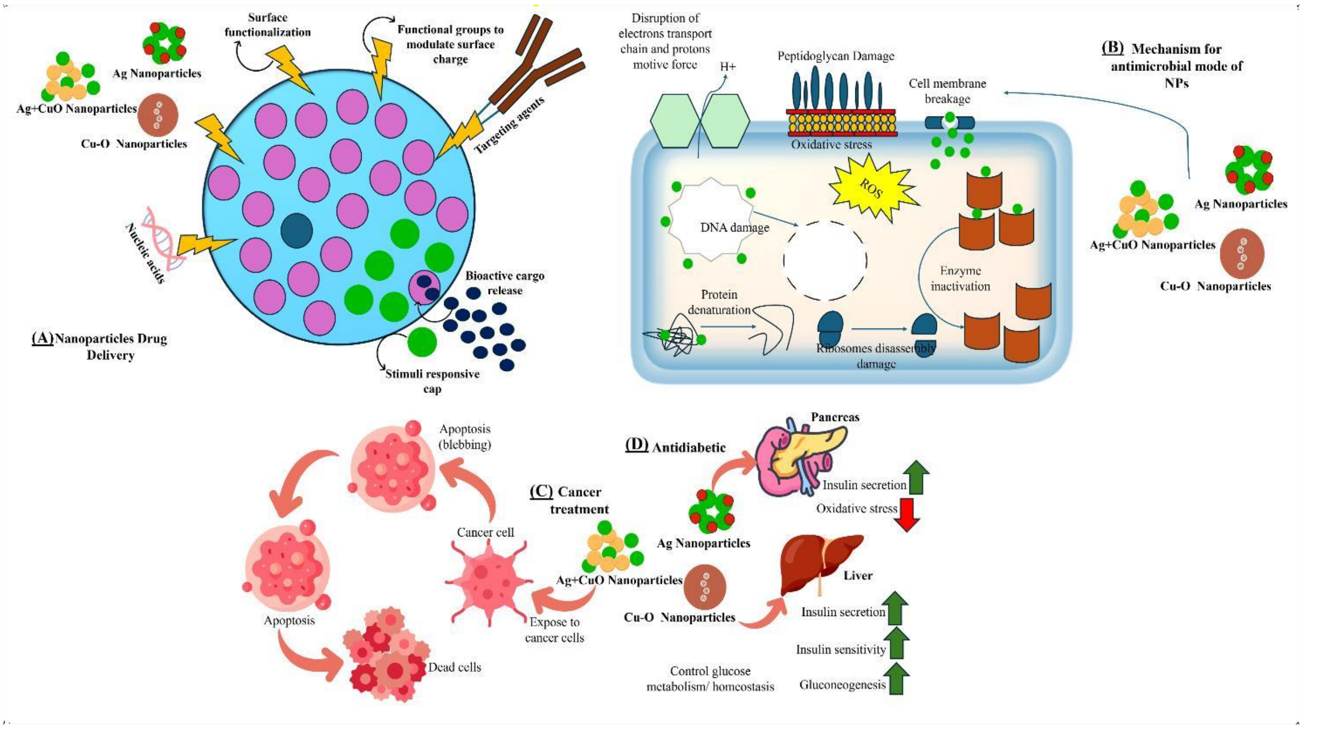

Fig. 3. Comprehensive mechanisms and applications of NPs: (A) Drug delivery mechanism of Ag, CuO, and Ag-CuO bimetallic NPs, showcasing surface functionalization, targeting agents, and controlled release of bioactive cargo. (B) Antimicrobial mode of action involving oxidative stress, DNA damage, protein denaturation, and cell membrane disruption. (C) Cancer treatment mechanism through nanoparticle-induced apoptosis and cancer cell death. (D) Antidiabetic effects of nanoparticles enhancing insulin secretion, sensitivity, and glucose metabolism by mitigating oxidative stress and regulating gluconeogenesis.

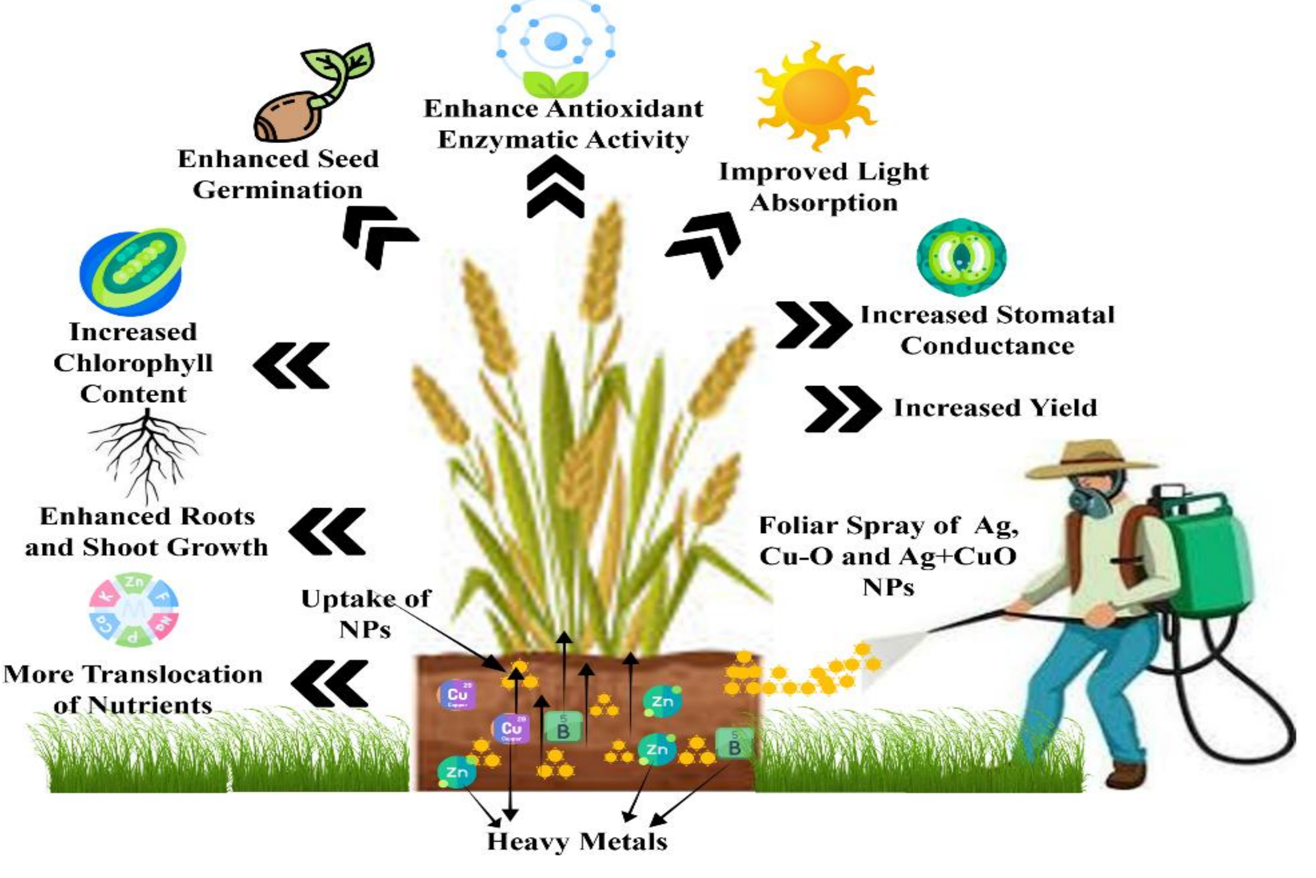

Fig. 4. Illustration of the agricultural benefits of plant-mediated NPs such as silver, copper, and Ag-Cu bimetallic NPs. Key effects include enhanced seed germination, improved root and shoot growth, increased nutrient translocation, elevated chlorophyll content, enhanced antioxidant enzymatic activity, improved light absorption, increased stomatal conductance, and higher crop yield. The diagram also depicts the uptake of NPs and their foliar spray application for sustainable agricultural practices.

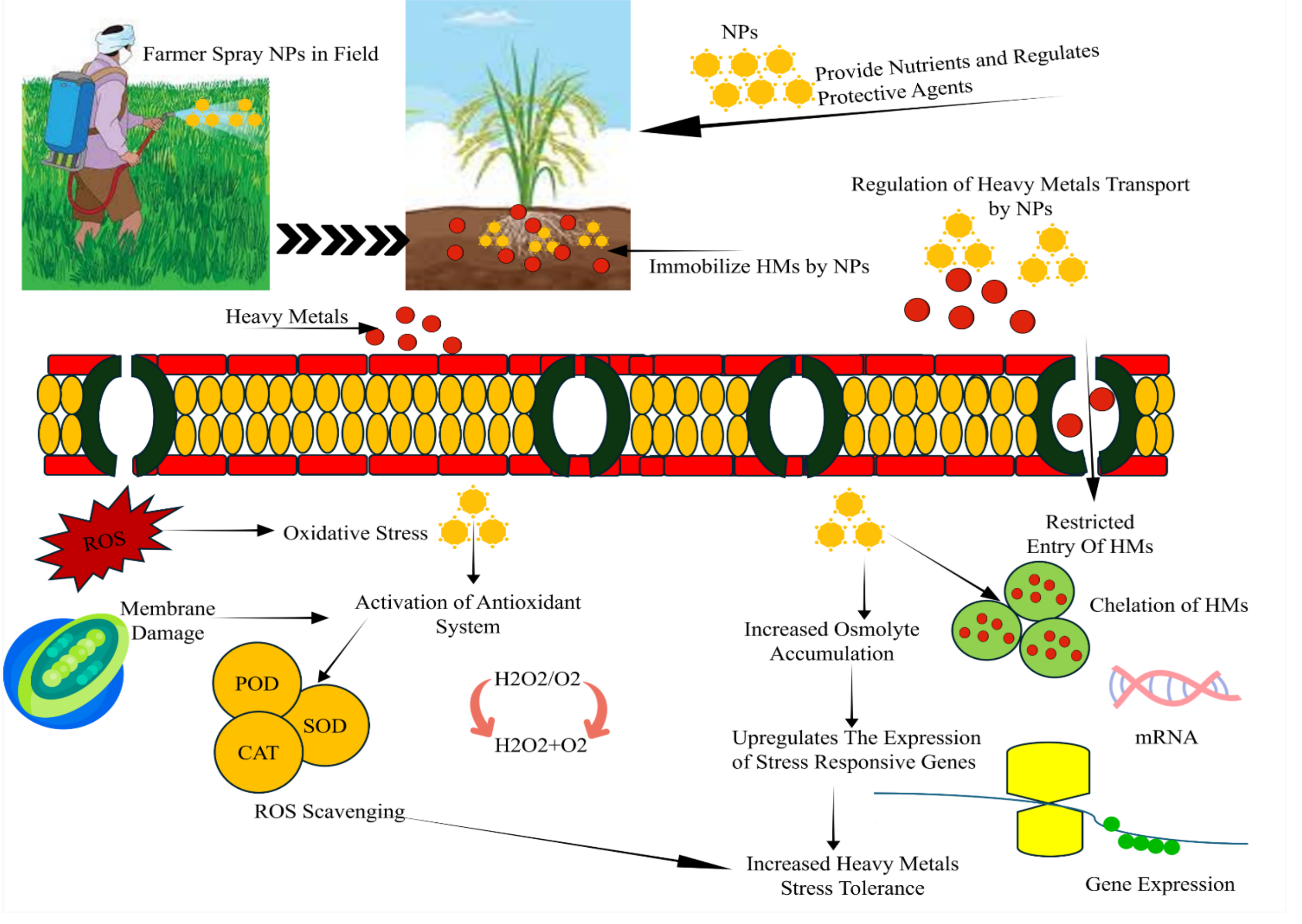

Fig. 5. Mechanism of plant-mediated NPs in mitigating heavy metal stress in crops. NPs regulate HM transport by immobilizing HMs in soil, restricting their entry into plant cells, and chelating excess HMs. They activate antioxidant systems (POD, CAT, SOD) to scavenge ROS, prevent oxidative stress, and protect cell membranes. Additionally, NPs increase osmolyte accumulation and upregulate stress-responsive genes, enhancing heavy metal stress tolerance and promoting plant health.

The use of plant mediated CuNPs like *Adhatoda vasica* and *Klebsiella pneumoniae* has been found to have large scale applications for reducing HM stress. These CuNPs enhance the physiological and biochemical characteristics of plants under stress by enhancing the antioxidant defense system, decreasing oxidative stress and controlling target HM transport genes. Copper NPs have increased photosynthesis efficiency and reduced cadmium and chromium uptake in the plant organs in both maize and wheat crops helpful in improving growth and yield in stressful environments (Noman *et al*., 2020; Tariq *et al*., 2021). Silver nanoparticles, extracted from *Ocimum basilicum* and *Trichoderma harzianum*, are particularly relevant to managing HM induced issues in crops such as cucumber and tomato. These AgNPs help in reducing the metal cadmium toxicity, seed germination, and increase antioxidant enzyme activity. AgNPs help to increase the resistance and yield of plants, stimulating metal transport genes and reducing oxidative stress even in case of saline and heavy metal influence (Shams *et al*., 2013; Krupa-Małkiewicz & Ochmian, 2024). Integrating silver and copper nanoparticles has shown great potential for enhancing plant characteristics and reducing HM stress. Growth improvement, increased oil quality, and yield of the phenotypic properties in *Brassica napus* have been promoted by foliar application of these nanoparticles. Besides, it can be mentioned that this dual application strategy not only enhances the HM stress tolerance but also promotes economic and environmental best practice in relation to agricultural practices (Rameen *et al*., 2024). Silver-copper bimetallic nanoparticles (Ag-Cu NPs) have shown promise in relieving stress from heavy metal toxicity in plants. They could sorb and remove toxic metal ions due to their physicochemical characteristics thus reducing phytotoxicity. For instance, Ag-Cu NPs prepared from *Catharanthus roseus* extracts have demonstrated the potential for the removal of cadmium and chromium from contaminated environments to promote plant growth and development in stressed conditions. The use of plant extracts in the biogenic synthesis of these nanoparticles presents a sustainable method for environmental cleaning (Verma & Bharadvaja, 2022). Figure 5 shows the mechanism of plant-mediated NPs in mitigating heavy metal stress in plants by regulating HM transport, activating antioxidant systems, and enhancing stress tolerance.

Nano-priming and foliar use of nanoparticles in the context of phytotoxicity and environment safety: Plant based NPs are eco-friendly and can help in enhancing resistance of crops and improvement in yield. NPs in foliar spray improve plants tolerance to abiotic stress like salinity and drought through improved photosynthesis, and chlorophyll content, and increased water-use efficiency without phytotoxic effects at recommended concentrations of ZnO and TiO_2 (Donia & Carbone, 2023; Yadav *et al*., 2024). Nano-priming with use of silica (SiO_2) or iron oxide (Fe_2O_3) nanoparticles increases germination, root development, and stress tolerance of seeds due to activation of ROS and increasing α-amylase activity, resulting in enhanced seedling performance (Hasanaklou *et al*., 2023; Tamindžić *et al*., 2023). However, deep precautions must be taken in the NP treatments and aim to balance the concentration in a way that phytotoxic effects can be avoided and no harm can cause to the long-term agricultural sustainability and ecosystem health of plant species (do Espirito Santo Pereira *et al*., 2021; Lee & Kasote, 2024). Nano-priming has been shown to have the feasibility of improving physiological and productive qualities in crops. Nevertheless, specific research has found that some concentrations and quantum-sized specifications of nanomaterials can exhibit phytotoxicity depending on the type of nanoparticles and the genetic difference of plants (Thuesombat *et al*., 2016; Kasote *et al*., 2021; Sharma *et al*., 2022). The present study indicates that further research on possible negative effects should be aimed at the identification of specific nanomaterials to be used and the proper dosing of these nanomaterials. At present, the impacts of widespread NP used in agriculture, especially in foliar application, are highly unknown concerning the NP soil deposits and ecosystem toxicity. Thus, it is very important to enhance the use of controlled and precise applications of NPs. Foliar methods give way to nano-priming as a better controlled technique that practically limits the detrimental effects of nano-ecotoxicity by confining exposure to the environment.

Prospects, key challenges, and future directions of green synthesis: The green synthesis of nanoparticles (NPs) holds significant potential in agriculture and biomedicine, offering opportunities alongside certain risks associated with their applications. In agriculture, green-synthesized NPs such as silver, copper, and bimetallic composites enhance crop yield by increasing the activity of antioxidant enzymes, improving photosynthesis, and reducing abiotic stresses such as heavy metal toxicity (Kumar *et al*., 2024; Murshed *et al*., 2024). These NPs are sustainable alternatives as they improve soil quality and utilize agricultural waste as raw materials for synthesis, promoting a circular economy (Krishnani *et al*., 2022; Su *et al*., 2024). In biomedicine, the biocompatibility of these NPs makes them suitable for applications in drug delivery, antimicrobial therapies, and cancer treatments. They exhibit enhanced interactions with biomolecules, improving therapeutic efficacy and precision. For instance, silver NPs have demonstrated exceptional antimicrobial activity, while copper NPs are effective in enzyme inhibition and oxidative stress regulation, contributing to their potential in advanced treatments (Sher *et al*., 2024; Wang *et al*., 2025).

Despite their promise, challenges remain in both sectors. In agriculture, the non-uniformity in size, shape, and activity of NPs, often caused by inconsistent synthesis methods, presents significant barriers to their widespread use (Senthamizh *et al*., 2025). Moreover, concerns about the toxicity of these NPs to non-target species and ecosystems highlight the need for comprehensive ecological risk assessments. In biomedicine, similar synthesis inconsistencies are compounded by challenges such as stringent safety regulations, high production costs, and the uncertainty of long-term effects, all of which limit their scalability and clinical application (Ma *et al*., 2024). Scalability is a critical limitation for the practical application of green synthesis outside laboratory conditions. Current biosynthesis methods are resource-intensive and lack cost-efficiency for large-scale production. Addressing these challenges requires interdisciplinary research and innovative solutions. For example, integrating artificial intelligence (AI) and machine learning (ML) into nanoparticle synthesis can enhance control over their size, shape, and activity while predicting potential toxicity for specific agricultural and biomedical applications (Xiao *et al*., 2024; Ashique *et al*., 2025).

Future research should focus on developing affordable, sustainable, and scalable green synthesis processes to meet the demands of both agricultural and biomedical applications. In agriculture, integrating green synthesis with precision farming offers promising opportunities to enhance food security, boost crop productivity, and ensure the sustainable development of farmland (Wahab *et al*., 2024). In biomedicine, advancements in green-synthesized nanoparticles (NPs) have the potential to revolutionize therapeutic formulations, making them more effective, safer, and environmentally friendly (Hade, 2025). Addressing regulatory challenges is critical for the successful implementation and commercialization of green-synthesized NPs. Establishing clear and robust regulatory frameworks will ensure their safe and ethical application, mitigate environmental risks, and promote human safety. Furthermore, efforts to bridge the gap between research and clinical translation are necessary to advance green-synthesized NPs from laboratory innovation to real-world applications. Strategies for commercialization, including cost reduction, public-private partnerships, and scaling production methods, will play a pivotal role in ensuring widespread adoption. With continued innovation, green synthesis can drive sustainable development in agriculture and medicine, contributing significantly to global ecological conservation and healthcare improvement.

Conclusions

Silver, copper, and their nanocomposites have the potential to revolutionize agriculture and the biomedical field by green nanotechnology using plant extract and agricultural waste. These nanoparticles increase yields, reduce the effects of adversity such as heavy metals and toxicity, and improve soil conditions; its pharmacological uses include a delivery system for drugs, an antibacterial agent, and a potential cancer fighter. However, challenges such as scalability, standardization, and potential ecological toxicity remain critical. Future research endeavors should focus on exploring biosynthetic pathways, precise regulation of plant mediated nanoparticles characteristics, and investigating the proteins and enzyme systems involved in their production. Additionally, it is crucial to comprehensively compare the properties of PMNPs with their chemically synthesized counterparts. Overcoming these barriers presents an opportunity to fully unlock the potential of bio-inspired nanoparticle synthesis, ultimately contributing to sustainable agriculture, advancing biomedicine, and benefiting future generations while aligning scientific progress with ecological preservation.

Acknowledgements

The authors would like to thank their respective institutions for their support. Authors would also like to thank the Molecular Systematics and Applied Ethnobotany Laboratory (MoSAEL), Department of Plant Sciences, Quaid-i-Azam University, Islamabad, for providing valuable resources.

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(Received for publication 20 November 2024)