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Green Synthesis of Silver and Copper Nanoparticles: Methods, Properties, Applications, and Environmental

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Silver and copper nanoparticles have attracted considerable research interest due to their diverse physicochemical properties and wide range of applications, particularly when synthesized using green approaches. This review summarizes literature published between 2000 and 2025 on the biosynthesis of silver and copper nanoparticles, with a focus on plant-mediated synthesis methods, synthesis mechanisms, physicochemical characteristics, applications, and environmental and toxicological considerations. Relevant studies were identified using keywords such as "green synthesis of nanoparticles," "silver nanoparticles," "copper nanoparticles," "characterization," and "environmental aspects." Plant-based synthesis commonly produces nanoparticles with acceptable stability and biocompatibility while reducing the use of hazardous chemicals. Silver nanoparticles demonstrate notable antimicrobial activity against a broad spectrum of microorganisms, whereas copper nanoparticles show potential in catalysis, electronics, and antimicrobial applications. Both silver and copper nanoparticles have been investigated for use in drug delivery, wound healing, and water purification, with their functional performance influenced by parameters such as particle size, morphology, structure, and surface chemistry. Despite the advantages of green synthesis, concerns related to toxicity and environmental impact remain. Available studies indicate that nanoparticle behavior and biological effects depend on concentration, exposure duration, and environmental conditions. Overall, green synthesis of silver and copper nanoparticles using plant sources represents a promising alternative to conventional methods; however, further systematic studies are required to better understand long-term safety and environmental implications.

Keywords: Antimicrobial; Characterization techniques; Copper nanoparticles; Drug delivery; Green synthesis; Nanoparticles; Silver nanoparticles.

Nanotechnology is a fast-growing area sector of science that understanding with materials at an extremely small scale—between 1 and 100 nanometers. At this level, materials show special properties like increased surface area and unusual chemical behaviour, which make them useful in medicine, electronics, environmental solutions, and material science. [1]Green synthesis is the promising way for the production of NPs, which uses natural sources like plants and microorganisms instead of harmful chemicals. This approach follows the ideas of sustainable chemistry, aiming to reduce pollution and make the process safer and more sustainable. [2] Now a days it is become more popular because traditional chemical methods often involve toxic substances and create harmful by-products. Among natural sources, plant extracts are mainly useful for nanoparticle synthesis. It contains phytocompounds that act as both reducing and stabilizing agents. Among all plant materials, *Caesalpinia bonducella* most suitable for synthesis of Cu as well Ag NPs. *Caesalpinia bonducella* commonly known as fever nut or nicker nut. It is well-known traditional medicine for its anti-Swelling, antidiabetic, as well as antimicrobial properties.[3] These medicinal effects come from bioactive compounds like bioflavonoids, alkaloids, and Isoprenoids, which also make the plant a strong candidate for nanoparticle production. Both types of nanoparticles have drawn interest because of their useful properties—silver for its antimicrobial strength and copper for its role in catalysis and electronics. By examining their synthesis, properties, and applications, this article highlights how green nanotechnology could offer eco-friendly solutions to current scientific and industrial challenges. [4] In addition, we will discuss how these Silver and Copper nanoparticles are studied through various characterization techniques, explore their possible uses in medicine and industry, and consider the environmental safety of their production and use. [5]This sets the stage for understanding how green nanotechnology can move forward responsibly while addressing real-world problems.

Green synthesis of copper and silver nanoparticles

Green Synthesis or Biosynthesis is a safer approach for making Silver NPs and copper NPs. [6] The green way of synthesis gained significant attention as scientists look for safer ways to create nanomaterials without harming the environment.[7] Many biological materials applicable for green approach synthesis of copper NPs as well as silver NPs, including plant derived compound extracts, together serve as a reducing as well as Stabilizing agents. This helps in generating a stable nanoparticle along with simplifies the production process. [2] It lowers the environmental impact. Since it relies on renewable and biodegradable resources, It reduces waste and pollution compared to chemical methods.[5-7] It also lowers the cost of waste disposal and can be more budget-friendly overall, as it uses easily available natural materials and requires less energy.[8] Because of all these above benefits, biosynthesis is becoming a preferred choice in the sector of nano-technology. Another key benefit is its low energy requirement. Most green approach of synthesis of silver NPs and copper NPs methods work at ambient condition or use low-energy tools like microwaves or ultrasound, which use much less energy than the high heat and pressure needed in traditional methods. These eco-friendly techniques also aim to reduce waste by adjusting reaction settings and making use of leftover materials whenever possible.[11] Various biological materials have been carried out successfully used in biosynthesis of Cu and Ag NPs due to their natural reducing and stabilizing capacity. Table 1 summarizes the major biological sources—including plants, microbes, algae, and biomolecules—commonly used for synthesizing nanoparticles, along with relevant examples and their key bioactive components. Several eco-friendly synthesis methods have been developed to replace energy-intensive and hazardous chemical techniques. Table 2 provides an overview of commonly used green synthesis methods, including aqueous, room temperature, microwave-assisted, sonochemical, and photocatalytic approaches, highlighting their advantages and applications.

Characterization of silver and copper nanoparticles

The characterization of AgNPs and CuNPs is crucial for understanding their physicochemical properties and potential applications. UV-visible spectroscopy is widely implemented to validate NPs configuration and evaluate their optical properties. AgNPs typically exhibit a SPR peak between 400-450 nm, while CuNPs show a broader peak around 560-580 nm. [23] Fourier transform infrared radiation spectroscopy helps identify the surface bond chemical groups present on the NPs surface, providing insights into the capping agents and potential interplay with biological systems.[24] XRD analysis is crucial for identifying the crystalline structure and phase homogeneity of Silver NPs and Copper NPs. AgNPs generally exhibit FCC structure with characteristic peaks at 2è values of 38.1°, 44.3°, 64.5°, and 77.5°, parallel to the (111), (200), (220), and (311) planes, respectively. [25]CuNPs also display an FCC structure with peaks at 43.3°, 50.4°, and 74.1°, representing the (111), (200), and (220) planes. SEM and TEM facilitate to give a majorly valuable information on nanoparticle morphology, size distribution, and aggregation state. AgNPs are often spherical or quasi-spherical, while CuNPs can exhibit various structured, including circle, 3 D square form , and rod-like shape. [26]

DLS and Zeta potential analysis offer crucial insights into the fluid dynamic dimensions and surface charge of NPs , respectively. These parameters notably impact the stability along with biological activity of AgNPs and CuNPs. Generally, AgNPs exhibit smaller hydrodynamic sizes (10-50 nm) compared to CuNPs (20-100 nm), while both types of nanoparticles typically display negative zeta potentials (-20 to -40 mV) in aqueous dispersions. [27] The morphological and optical characteristics of AgNPs and CuNPs act as a vital role to identify their biological activity, particularly in antimicrobial and anticancer applications. Decreased size of NPs with higher SA : V ratio tend to indicate improved antimicrobial efficacy due to maximized cellular absorption and synthesis of ROS. Additionally, the SPR characterization of AgNPs and CuNPs contribute to their photothermal effects, which can be exploited for targeted cancer therapy. [28] The table 3&4 illustrates Studies example for characterization silver nanoparticle and copper nanoparticle. The sequential steps involved in nanoparticle characterization are depicted in Figure 1.

Opportunistic bioactivities of copper and silver nanoparticles

Silver and copper nanoparticles' broad-spectrum bioactivities imply that they have the ability to alleviate various disorder. It mainly used for cancer management, Infectious disease management, cardiac disorder and various genetic disorder. Both NPs play an vital role in therapeutical sector. Studies are going for enhancing the both copper and silver nanoparticle for the application of therapeutical sector. The following table 5&6 illustrate the studies examples bioactivity studies of both silver and copper nanoparticle. [43,44] The diverse biological applications of nanoparticles are summarized in Figure 2.

Antimicrobial activities of the nanoparticles

The rise of multidrug resistant microbes has prompted the exploration of alternative anti-microbial agents, with nanoparticles emerging as a promising solution. NPs contain specific physiochemical characteristic , including very less and controllable size, large SA : M , and high activity , which can be leveraged to prevail overcome the limitations of conventional antimicrobial therapies. [55,56]These properties enable nanoparticles to promote the delivery of antimicrobial therapeutic agent, so it enhancing their effectiveness against a broad spectrum of bacteria. [57] The antimicrobial properties of NPs penetrate biological membrane of bacteria, manipulate cellular processes, and produce ROS that lead to cellular damage and its apoptosis. [55,58] The World wide emergence of muti drug resistant microbes has made the traditional treatment of infectious diseases increasingly challenging, underscoring the urgent need for another anti-microbial strategies. [58]

Silver nanoparticle have garnered notable attention as potent antimicrobial substances due to their broad range of effective Anti-bacterial, Anti-fungal, and Anti-viral activity. [59]Ag NPs can crossing the bacterial cell wall penetrate bacterial cell walls, alter cell membrane structure, and interfere with cellular mechanism, finally results to cell apoptosis. The potential of Ag NPs is attributed not only to their nano measurement size but addition to their Increased SA : V which improves their capability to react with disrupt the microbes.[60] The antimicrobial mechanism of both silver and copper nanoparticles is illustrated in Figure 3. Table 7& 8 depicted the studies examples for Anti-microbial activities of Silver and copper nanoparticles.

Environmental and its toxicological aspects of green synthesis of copper and silver nanoparticles

Green synthesis Nanoparticle have a variety of uses. But it have some environmental restrictions. And the majority of studies showed that green nanoparticles have several advantages in medicine over other nanoparticles, but the facts are that green nanoparticles have toxicity just like other nanoparticles, but the toxicity is limited in comparison to other nanoparticles, and few studies show that there are no well-studied papers on green nanoparticle toxicity. [37]

Environmental aspects of green nanoparticle

Green nanoparticles have various purpose environmentally. The major purpose are water treatment, Agriculture fertilizer, Soil remediation and Oily sewage remediating agent. Although it is safer for disposal because of no harmful chemicals are used.

Water treatment and purification

Nowadays it is essential to purify drinking water because water from various sources may include hazardous amounts of organic compounds, heavy metals, and bacteria. Water for domestic use is purified using techniques like coagulation, filtration, settling, chlorination, and other chemical methods. Inorganic anions, heavy metals, organic contaminants, and bacteria have all been successfully removed from water using AgNPs and CuNPs that are more stable, economical, and have a controlled release rate. These AgNPs have demonstrated encouraging promise for use in the treatment of water and wastewater. The extreme toxicity to microbes has led to an increase in their use for water disinfection

Table 1. Biological Sources for Green Synthesis of Nanoparticles

Source Type	Example	Key Compounds & Benefits
Leaf extracts	*Azadirachta indica*, *Ocimum sanctum*, *Camellia sinensis*	Rich in bioflavonoids, isoterpenoids, and antioxidant compounds; act as reducing and stabilizing agents.[12]
Fruit extracts	Lemon, orange, pomegranate, grapes	High in vitamin C and polyphenols; effective for silver and gold nanoparticle production.[13]
Root and stem extracts	Ginger root, *Aloe vera* stem	Contain unique phytochemicals; used for synthesizing gold and silver nanoparticles.[14]
Bacteria	*Pseudomonas stutzeri*, *Bacillus subtilis*	Produce nanoparticles either intracellularly or extracellularly; scalable and consistent.[15]
Fungi	*Fusarium oxysporum*, *Aspergillus fumigatus*	Tolerant to metals; produce stable nanoparticles with good size and shape control.[16]
Algae	*Chlorella vulgaris* (microalga), *Sargassum wightii* (macroalga)	Fast-growing and abundant; suitable for eco-friendly nanoparticle synthesis.[17]
Proteins/Enzymes	Bovine serum albumin (BSA), nitrate reductase	Biocompatible coatings; promote safe nanoparticle formation.[18]
Polysaccharides	Chitosan, starch, cellulose	Natural stabilizers and reducers; increase stability and biocompatibility.[19]

Table 2. Green Synthesis Methods for Nanoparticles

Method	Description	Benefits
Aqueous medium synthesis	Uses water as the main solvent with biological extracts added to metal salt solutions	Simple, safe, and avoids harmful organic solvents.[1]
Room temperature synthesis	Uses plant or microbial extracts at ambient temperature	Energy-saving; suitable for heat-sensitive biomolecules.[2]
Microwave-assisted synthesis	Applies microwave energy to speed up reactions	Quick, uniform heating; reduces synthesis time.[20]
Sonochemical synthesis	Uses ultrasound waves to create localized energy for reducing metal ions	Produces nanoparticles with controlled size and shape.[21]
Photocatalytic synthesis	Uses light energy and photosensitive biomolecules to form nanoparticles	Environmentally friendly; allows solar-based synthesis.[22]

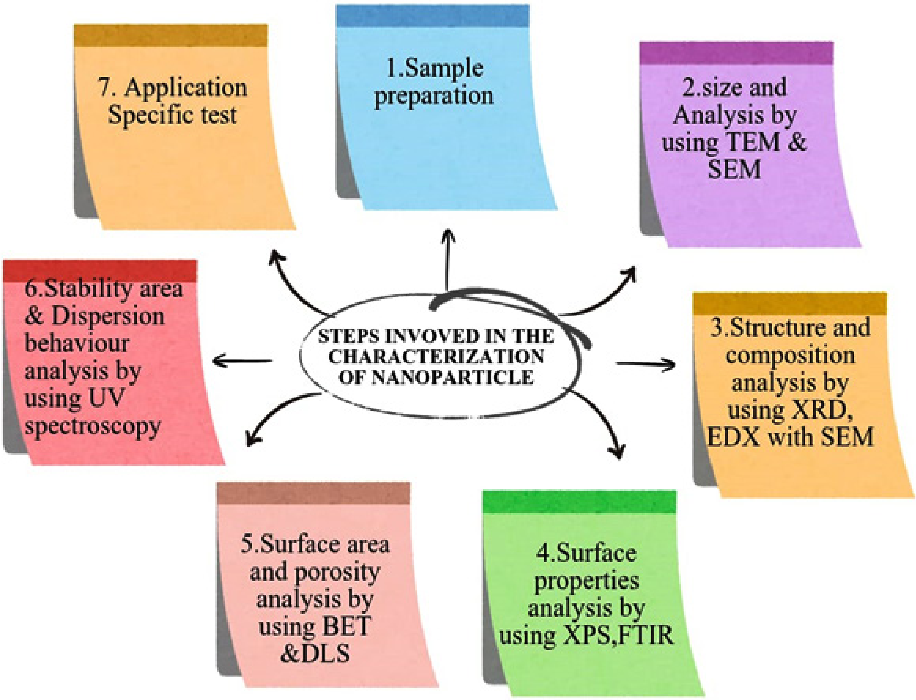

Fig. 1. Steps Involved in Characterization of Nanoparticles

in recent years. However, direct application of AgNPs may cause them to aggregate in aqueous conditions, which would gradually lower their effectiveness over time. According to several research, AgNPs affixed to filter materials may be a preferable option in this situation to reduce the aggregation issue and be economical with effective antibacterial potential. Significant antibacterial capabilities against E. coli have been demonstrated by the sheets where AgNPs are placed on the cellulose fibers. Furthermore, the standard range of Ag+ in drinking water (0.1 ppm) established by the WHO and environmental protection agency is not exceeded by the loss of Ag+ from such sheets. Furthermore, over the past 20 years, there has been an increase in the efficient use of Ag NPs implanted on ceramic materials or membranes for the disinfection and treatment of domestic water at the point of use. Preventing membrane filter fouling in water treatment systems is yet another application for AgNPs. A study performed by Das and colleagues . discovered that Copper oxide NPs isolated from the extract of Madhuca longifolia plant had good photocatalytic activity for dissolving methylene blue dye. As a result, it offers excellent photocatalytic potential for wastewater treatment. [79-81] Another work employed Jatropha curcas L. extracts to make TiO2NPs. That study discovered the Titanium dioxide Nanoparticles are effective in the potential photocatalytic treatment of wastewater. The NP eliminated 82.26% of COD and 76.48% of Cr from contaminated water.[82]

Nano-fertilizer

Bio- and nano-fertilizers are sustainable materials that may provide plants with essential nutrients, promote plant development, and boost agricultural yields. Biofertilizers, often known as bacterial fertilizers, use living or inactive microorganisms to promote plant development. [83]Nanofertilizers are classified into three types: (i) NPs, which include nanoparticles such as Tio2, silica compounds , and Nanotube form of Copper and promote plant development; (ii) essential nutrients in the micro form , which include Cu, Zn, Fe, Mo, Ni, and Mn; and (iii) essential nutrients in the form of macro, which combine Po4, Ca, N2, and K. Several, studies shows that phosphatic fertilizers in nano form increased soybean growth

Table 3. Studies example for characterization of silver nanoparticle

Author name	Material used for Synthesis of AgNPs	Surface Plasmon Resonance (SPR)	Shape and Morphology	Zeta potential	Size	Size Distribution	Crystal Structure	stability
Iwuji C et al[29]	Trisodium citrate	Nil	Spherical with consistent morphology	Nil	58.3 nm	Uniform size distribution	Nil	Nil.
Asif M et al[30]	Moringa olifera leaves	419 nm	Spherical	Nil	18 nm	10-25nm	Nil	Nil.
Liaqat N et al[31]	Eucalyptus camedulensis, Terminalia arjuna and their combination	410- 430 nm	spherical	-26 mV ± 4.61 mV; — 20 mV ± 5.09 mV; -27mv respectively	37,46,80 nm	Nil	Nil	Strong stability for 30 days.
Baran MF et al[32]	Alium cepa (yellowish peel)	438.90 nm	Spherical	– 13. 1 Mv	8.44-19.93 nm	Nil	cubic	Nil.
Khane Y et al[33]	citrus limon zest extract	535.5 nm	Spherical	– 21.5 Mv	7-28 nm	Nil	FCC	Nil.
Reddy NV et al[34]	perilla frutiscens leaf extract	Nil	Spherical, rhombic, triangle and rod	– 25.83 Mv	20-50 nm	Nil	FCC	Stable b/w 20 and 900 degree celsius by TG analysis.
Giri AK et al [35]	Eugenia roxburghii DC	417 nm	Spherical	– 37.8 Mv	24nm		FCC	Nil

by 32% and seed output by 20% when compared to traditional fertilizers. [84]De Franca Bettencourt and colleagues. used green-synthesized AgNPs from onions as a nano form of Biofertilizer for brinjal and tomatoes. Silver nanoparticles were sprayed on the green plants at doses ranging between 5 to 15 mL/L. Raising the nano-fertilizer concentration to 15 mL/litre increased the plant's effectivity and strength. This outcome can be attributed to onions' richness of proteins, phosphorus, carbs, and potassium, all of which can help plants development. [85] Nanofertilizers can not only assist plants survive with numerous stressors including parched condition, infection, and parasites, but they can also cause a variety of biological oriented chemical responses in the body including increasing the plant's immunological capability as well as promoting the synthesis of auxin. Furthermore, the usage of nanofertilizers helps to boost nutrient solubility in the soil, which improves soil natures and production while also encouraging healthy strong plant development. These ecologically friendly fertilizing agents are created using simple as well as quick procedures. A variety of strategies can be used to stimulate plant growth. [86]

Soil remediation

The problem of severe soil pollution became worse over time, with increasingly negative consequences for both environmental and human biological origin. Several strategies are used to remediate soil contamination, such as decontamination recovery. But those methods are time-spending, expensive, and extremely hazardous. It leads to, in situ treatment methods, including the introduction of NPs into the soil, have profitable appeal. Particular green NPs have proven extraordinary success in the recovery of soil impurities such as Strain materials and heavy metals. This is related to their increased mobility, extraordinary responsiveness, less amount of lethal effect, and enough amount of large surface areas. [87] Zaki et al.[89] used biogenic NPs synthesis Zno from Trichoderma harzianum as an fungicidal opposed to soil microbes including Macrophomina phaseolina, Rhizoctonia solani, and Fusarium sp. in different cotton cultivars. Zno antifungal impact varied by cotton cultivar, with Giza90 showing better plant life, length, and weight. This suggests that zinc oxide at 200 ig/mL is highly effective in

Table 4. Studies examples for Characterization of Copper NPs

Author name	Material used for Synthesis of CuNPs	Surface Plasmon Resonance (SPR)	Shape and Morphology	Zeta potential	Size	Size Distribution	Crystal Structure	stability
Nagar N et al[36]	Azadirachta indica	560 nm	Cubical	-17.5 Mv	48 nm	Nil	FCC	Stable for 2 months verified by the contrasting FITR spectrum of herbal neem and biologically reduced synthesised CuNP.
Mali SCet al[37]	Celastrus paniculatus bioactive leaf essence.	Nil	Spherical	-22.2 Mv	2-10 nm	290 nm	Nil	Stability of CuNPs is Confirmed by DLS.
Ismail MIM et al [38]	Aqueous Rhus coriaria L. fruits	568 nm	semi-spherical	Nil	14-24 nm	Nil	FCC	Nil.
Hasheminya et al [39]	Eryngium caucasicum Trautv	580 nm	Almost spherical	Nil	< 40 nm	Nil	FCC	Nil.
Wu S et al[40]	C. vitiginea	340 nm	Spherical	Nil	10-20 nm	Nil	Nil	Nil.
Caroling GM et al[41]	Aqueous guava extract	570 nm	spherical shape	Nil	Nil	Nil	FCC	Cu NPs that are moderately stable for fifteen days at ambient temperature with no evidence of precipitation.
Amer MW et al [42]	Citrus limon fruits separate	579 nm	spherical	Nil	18 nm	5-28 nm	Nil	Nil.

FCC – Face centred cubic, CuNPs – copper nanoparticles disease prevention. Using 200 ìg/mL of zinc oxide increased plant survival in the Giza94 cultivar, however disease control did not improve survival rates. Nonetheless, zinc oxide demonstrated superior improvements in the strength and length of the Giza94 cultivar. [88] Furthermore, Kalaba and the colleagues employed biologically prepared ZnO derived from S. plicatus to suppress plant microorganisms. The demonstrated findings showed that Meloidogyne incognita had a good mortality rate of 96.7% within 3 days. ZnO increased Vicia faba seed development at concentrations ranging from 12.5-50 ìg/mL. biosynthesis NPs have shown extraordinary success in soil recovery, notably in reduce the heavy metals including Cd, Ni, Ar, and Cr from polluted soils. Furthermore, these NPs have strong antibacterial effects on many plant diseases, altering plant weight, length, and overall life. [89]

Oily sewage remediating agent

Silver and copper nanoparticles are important components in oily sewage cleanup solutions because of their antibacterial, catalytic, and antifouling capabilities. They improve treatment efficiency by disturbing oil-water emulsions and limiting bacterial development, which causes fouling in wastewater systems. Silver nanoparticles in nanocomposite membranes prevent membrane fouling during oily wastewater filtration, thus enhancing oil particle removal. Silver nanoparticles added into remediation agents target oily sewage by boosting photocatalytic destruction of organic contaminants and stabilizing emulsions to facilitate separation. Biogenic silver nanoparticles derived from plant extracts promote the breakdown of oily pollutants in industrial effluents. They also have a great capability for adsorbing heavy metals and oils found in sewage.[90,91] FeNPs produced from Vaccinium floribundum were used to measure the elimination of TPHs from H2O . This leads to demonstrated that the reducing condition produced by iron nanoparticles resulted in improved TPH elimination (88.34%). [92]

Toxicological aspects of green syntesis of copper and silver nanoparticles

Bio synthesis of CuNPs and AgNPs have been beneficial in a variety of a usage due to their size, shape, and catalytic behaviour. However, these features may be unfavourable because their action as an antibacterial agent is not selective to microbes, resulting in a high likelihood of lethal action on human body . This is because of the fact that bio synthesis of cu and Ag NPs have the same size as biological compounds such as group

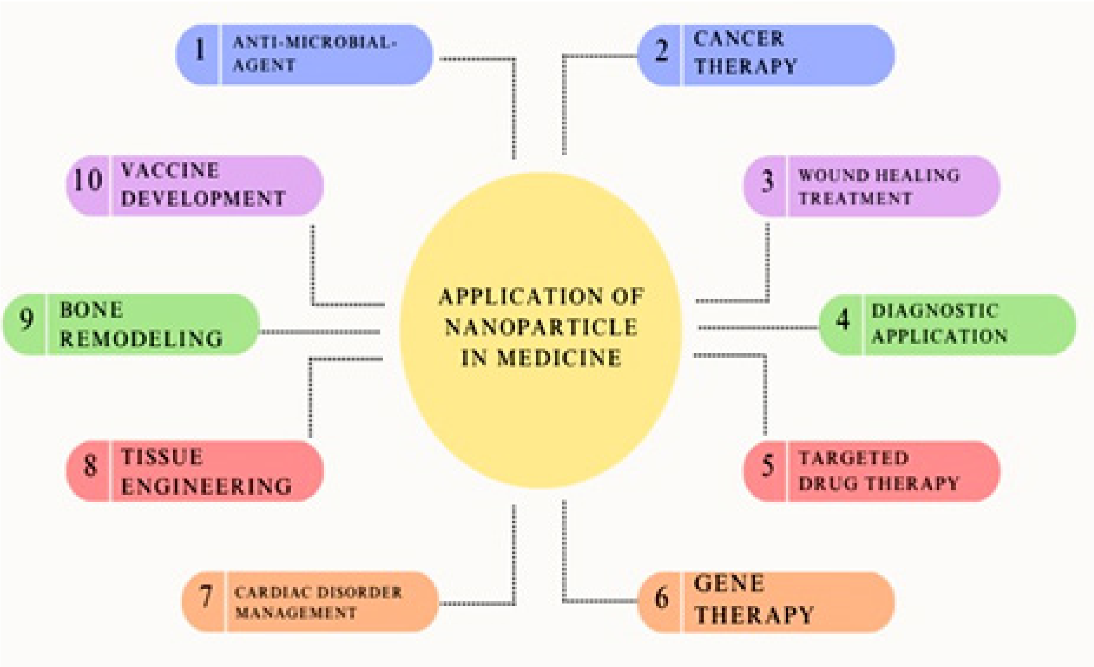

Fig. 2. Biological Application of Nanoparticle

of amino acids, Deoxy Ribo nucleic acids, and enzymes, allowing for easy entrance into live cells and the circulation, from whence they can spread to other body parts. [93]The tiny green 865 particles may induce cell membrane destruction, oxidative Deoxy Ribo Nucleic Acid destruction, and disrupt the ETC since they have permeability potential to cell materials and leads to harm when present over a certain threshold. But, the exact inhibitory action has yet to be determined due to a lack of evidence on green nanoparticles' biological related Response, transport, metabolic process, and organ-specific toxicity mechanism. [94]

Based on size, morphology and surface charge

Less Size particles have discovered a clear correlation together with their oxidative effectiveness, genetic cell having destruction capacity, and biological behaviour. Particles <50nm are harmful to almost all kinds of cells. [95] These green NPs can remain suspended in the marine and air environments for extended periods of time, exposing live creatures for prolonged periods of time and increasing toxicity. [96]The form of nanoparticles (circular, triangular, star, and tubular) has been shown to alter endocytosis and phagocytosis. [97] Circular-NPs were discovered to be simply endocytosed. [98] The particle's surface energy has a strong impact on its aggregation response, which in turn influences toxicity. Furthermore, the surface coat of an organic chemical on a green synthesis of copper and Silver NPs may modify its reactivity, surface energy, surface toughness, and pore shape, either eliminating or inducing toxic properties based on the kind of covering. [97]

based on composition of nanoparticle

Certain aspects of NPs, such as their solubility, surface features, and dosage, might cause lethal effect. These characteristic may promote (i) oxidization depression through the generation of reactive oxidative sp , which affect the group of involved in damage restore, cell wall damage, exduation of cellular compounds,

Table 5. Studies examples for bioactivities of copper nanoparticles

Author Name	Material used of synthesis of CuNPs	Bio-activity
Raffi M et al [45]	Inert gas Condensation process	Cu NPs show full cytotoxicity against E. coli.
Zhao H et al [46]	Allium eriophyllum Boiss	Anti-bacteria Anti-fungi, and cutaneous wound healing action.
Das Jana I et al [47]	Transparent coating of Cu-Gr	Cu-Gr nano Shows familiar Viricidal action in the solid state.
Ahmadi M et al [48]	Juglans regia green husk marine essence	Docking studies indicated that the synthesized CuNPs may bind with the Herbie simplex virus-1 glycoproteins and disturb with viral entry.
Al-zharani M et al [49]	Electroless Deposition Process	Exposing breast and colon cancer cell lines to cu NPs caused cytotoxicity and apoptosis.
Ramyadevi J [50]	Polyol process	Mosquito larvicidal agent.
Mali SC et al [37]	Celastrus paniculatus leaves extract.	Antifungal efficacy against F. oxysporum.
Hasheminya SM et al [39]	Eryngium caucasicum Trautv	Antioxidant and Antibacterial characteristic.
Wu S et al [40]	Cissus vitiginea	Enhanced bacteriostatic and ROS quenching agent against UTI germ and 2,2- diphenylpicrylhydrazyl reactive species.
Caroling G et al [41]	Aqueous guava isolate	Copper nanoparticles disturbing the cell membrane of bacteria by releasing Cu ions.

Table 6. Studies example for Bioactivity of Silver Nanoparticle

Author Name	Material used of synthesis of Ag NPs	Bio-activity
Sundar JS et al [51]	Caesalpinia bonducella seed	Good bactericidal activity against both gram negative strain bacteria and gram-positive strain bacteria.
Sundar JS et al [51]	Caesalpinia bonducella seeds	Inhibition of breast malignant Hca 7 cells. AgNPs may be a bioactive contender for breast malignant therapy.
Singh P et al [52]	Prunus serrulate	Anti- edematus activity in RAW264.7 cell lines through in vitro tests.
Zhang P et al [53]	Teucrium stocksianum and moringa oleifera	Anti-leishmanial activity and Anti- malaria.
Rai M et al .[54]	Biological synthesis	Biologically produced AgNPs show potent acaricidal, larvicidal activities and preventing the expand of vector-borne diseases.
Khane Y et al [29]	Trisodium citrate	Ag NPs shows bactericidal agents in the treatment of hospital-acquired illnesses.
Iwuji C et al [30]	moringa olifera leaf	Ag NPs were found to be potent active against E. coli, which is tolerance to most marketly available antibiotics.
Asif M, et al [33]	citrus limon zest extract	strong bacteriostatic action against E. coli and S. aureus, along with fungicidal efficacy opposed C. albicans and Strong antioxidant action.
Reddy N et al [34]	perilla frutiscens leaf extract	Antibacterial, antioxidative, and anticancer properties.
Giri AK et al [35]	Eugenia roxburghii DC	AgNPs against bacterial biofilm development.

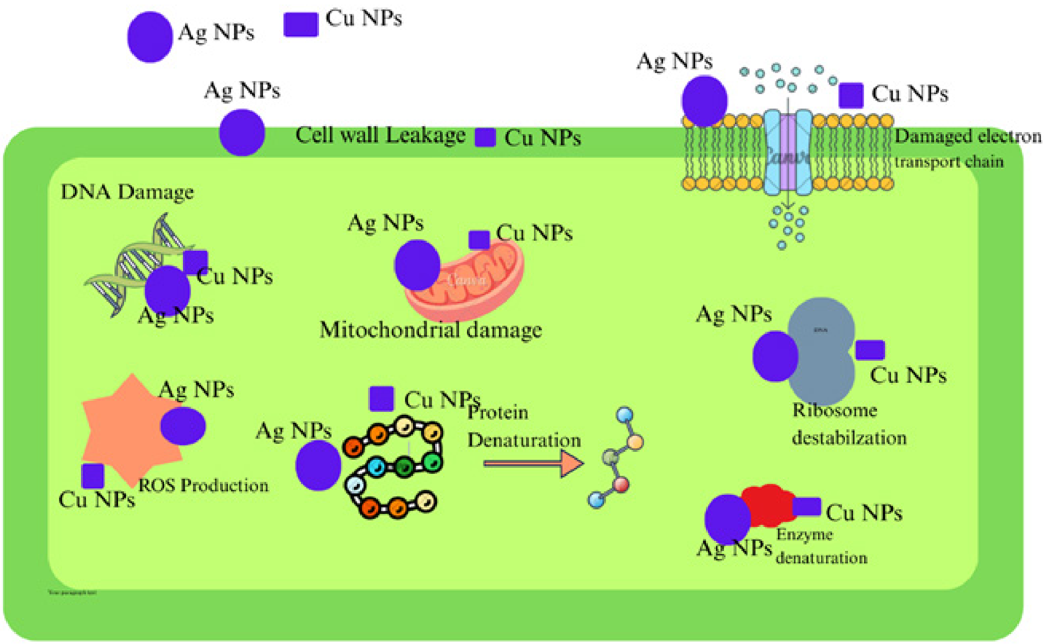

Fig. 3. A schematic representation antimicrobial activity of Both Silver and copper nanoparticles

Table 7. Studies example for Anti-microbial activity of silver nanoparticles

Author Name	Material Used for synthesis of AgNPs	Test organism	Results
Rahman H et al [61]	Rhazya stricta Decne Extract.	Bacterial agents: S.aureus, and Salmonella typhi, E. coli. Fungal agents: C. albican, Trichophyton longifusis, F. solani.	Good anti-bacterial and anti-fungal activity.
Yu Z, et al [62]	Black rice (O. sativa)	S. aureus, E. coli	Good bactericidal activity.
Avilala J et al [63]	Marine actinomycetes	Bacterial agents: P. aeruginosa, S. aureus, E.coli, Klebsiella pneumonia and B.subtilis Viral Agents: Lasota strain of Newcastle Disease Virus	Good bacteriostatic along with anti-viral activity.
Ullah I et al [64]	Peganum harmala L. extract	Bacterial agents: Staphylococcus aureus *Pseudomonas aeroginosa*, Salmonella *typhi*, and Escherichia coli Fungal agents: candida albicans and *Aspergillus Niger*	Good ant-bacterial and anti-fungal activity.
Amara YT et al [65]	Mentha aquatica	E.coli, S. Aureus, P.aeruginosa	Good bactericidal against based on its concentration.
Vijapur LS et al [66]	Cinnamomum tamala.	Gram – ve microbes: E. coli along Klebsiella pneumonia Gram+ve microbes: S. mutans and Enterococcus faecalis	Highest antimicrobial activity against E. coli. Among all microbes.
Samad M et al [67]	Dicliptera bupleuroides Nees	gram +ve pathogens B.subtilis, Enterococcus faecalis and S.aureus and gram -ve stain such as K. pneumonia and E. coli	Highest microbicidal activity against B. subtilis and minimum against E. coli.
Kemala P et al [68]	Calotropis gigantea leaves and flowers	Bacterial pathogen: E. coli and S. aureus, Fungal pathogen: C. albicans,	Flower extract produces good anti-microbial activity compare to leaf extract. Because the flower contains flavonoids.
Khane Y et al [33]	Aqueous Citrus limon Zest extract	Gram – ve microbes E. coli, Gram + ve microbes S. aureus, and fungal stain C. albicans.	Anti-bacterial activity. Gram – ve pathogens were more susceptible than Gram +ve strains.
Keshari AK et al .[69]	Cestrum nocturnum	Citrobacter, Enterococcus faecalis, Escherichia coli, Pseudomonas vulgaris, Salmonella. typhi along with Vibrio cholerae	Anti-bacterial against Enterococcus. faecalis and Vibrio cholerae.

Table 8. Studies example for Anti-microbial activity of copper nanoparticles

Author Name	Material used for synthesis of CuNPs	Test Organism	Results
Prakash MD et al [70]	Tinospora cordifolia leaves	Bacterial Pathogen: Lactobacillus Species, S.aureus, and Streptococcus mutans,Fungal pathogen: C.albicans	Good Anti-bacterial action and good anti-fungal activity
Jahan I et al[71]	Citrus sinensis aqueous fruit extract in microwave mediated	S. aureus, Escherichia coli	Strong Anti-bacterial action against gram +ve bacterial microbes compare to gram -ve microbes.
Ha T et al [72]	High energy electron beam process	H1N1 influenza virus.	Good anti-Viral activity
Punniyakotti P et al .[73]	Cardiospermum halicacabum	Psudomonus aeruginosa, Escherichia coli, and S. aureus,	Good bacteriostatic and anti-biofilm suppressive agent formation activity in both gram + ve and gram -ve bacteria.
Prasad R et al [74]	Musa acuminata and Citrus sinensis Peel Extracts	Bacterial agent: Escherichia coli, Staphylococcus aureusFungal agent: Aspergillus Niger	Dry orange peel extract had better antimicrobial activity than the fresh orange peel, dried banana peel, fresh banana peel.
Jothiramalingam R et al[75]	Lemon flower extract	Salmonella typhi, Streptococcus mutants, E.coil, Staphylococcus aureus and Psudo monus aurugenosa.	Higher anti-bacterial activity at very low concentration.
Jayarambabu N et al [76]	Curcuma longa extract	Gram positive and Gram-negative microbes	Good anti bacterial activity opposed to action against both gram +ve and Gram -ve bacteria.
Hamad AM et al [77]	strawberry leaves.	S. aureus and P. aeruginosa, obtained from corona Virus affected Patients	Gram- +ve strain bacterial microbes were more responsive to copper nanoparticles than Gram -ve strain bacterial microbes. Due to difference chemical composition present in bacterial cell wall.
Ramasubbu K et al [78]	Sesbania grandiflora Leaf Extract	Escherichia coli , Psudomonas . aeruginosa, S. Aureus	Better anti-bacterial activity compared to streptomycin
Wu S, et al [40]	Cissus vitiginea	UTI microbes such as E.coli, Enterococcus sp., Proteus species. and Klebsiella species.	Good Anti-bacterial activity against UTI Pathogens.

and swelling action, or (ii) genetic toxicity.[99]The vigorous effects of these Bio NPs on organisms may be assessed using cell culture and whole organism studies in toxic to cells experiments. Cytotoxic processes in tumour therapy and drug delivery such as the formation of Reactive oxygen species , the action of cell death effector enzymes , the deactive of enzymes, and the dose-related suppression of Adenosine triphosphate synthesis, all of which lead to cell death. [100] Particularly, Copper nanoparticles are generally more harmful than silver nanoparticles across a variety of biological systems, owing to increased reactive oxygen species (ROS) production and metal ion leaching, which are regulated by their composition and surface stabilizers. Silver nanoparticles (AgNPs) exhibit lesser human cell toxicity but robust antibacterial activity, whereas copper nanoparticles (CuNPs) produce more ROS in both mammalian and bacterial cells, with PVP-stabilized CuNPs being particularly harmful.[101]

Future perspectives

The future of green nanotechnology, particularly in the synthesis of AgNPs and CuNPs with opportunities for innovation and development. Key areas for future exploration include:

Optimization of Synthesis Protocols

Refining green synthesis of copper and silver nanoparticle techniques to target precise monitoring over nanoparticle size, structure, and composition. This may involve experimenting with combinations of plant extracts or optimizing reaction conditions for higher yield and reproducibility.

Mechanistic Insights

Investigating the underlying mechanisms of nanoparticle formation, including the role of specific phytochemicals in reduction and stabilization, to develop more efficient synthesis strategies.

Scalability and Industrial Applications

Addressing challenges related to scaling up green synthesis methods for industrial production, including cost-efficiency, quality control, and consistency.

Advanced Functionalization

Exploring methods to functionalize green-synthesized nanoparticles with biomolecules or synthetic compounds to broaden their applications, particularly in targeted drug release and biosensing.

Combination Therapies

Studying the enhanced combined effects of NPs with conventional therapies, such as antibiotics or anticancer drugs, to enhance treatment efficacy.

Ecological Recovery

Expanding the use of green-synthesized NPs for cleaning up pollutants, including bioaccumulate metals and organic contaminants, in water and soil.

Nanosensors & Diagnostics

Developing highly sensitive and specific diagnostic tools and environmental sensors using green-synthesized nanoparticles for early disease detection and monitoring.

Artificial Intelligence Integration

Leveraging AI and machine learning to optimize nanoparticle design and synthesis, accelerating the discovery of materials with enhanced properties.

Standardization and Regulation

Establishing clear guidelines and regulatory frameworks for the properties , testing, and application of biosynthesized NPs to ensure safety and consistency.

Long-term Toxicity Studies

Conducting expensive research studies on the long-period impacts of Nano particle on human along with ecosystems to promote responsible development.

Biodegradable Nanoparticles

Developing biodegradable nanoparticles through green synthesis to address environmental concerns and enhance their suitability for biomedical applications.

Agricultural Applications

Exploring the uses of biosynthesized NPs in Farming , such as nanoscale fertilizers and nano formulated pesticide , to promote sustainable farming practices and improve food security.

CONCLUSION

Bio-nanotechnology, particularly the green synthesis of silver and copper nanoparticles, represents a viable and increasingly explored approach for addressing challenges across biomedical and environmental applications. The analysis presented in this review highlights the potential of Ag and Cu nanoparticles in areas such as antimicrobial activity, drug delivery, wound healing, and water purification, while emphasizing advantages associated with green synthesis, including improved biocompatibility, reduced use of hazardous chemicals, and cost-effectiveness. Advanced characterization techniques have played an important role in understanding the physicochemical properties of these nanoparticles, including size, morphology, surface chemistry, and stability. Such insights are essential for optimizing synthesis protocols and tailoring nanoparticles for specific applications. Green-synthesized Ag and Cu nanoparticles show promising antimicrobial properties, particularly against drug-resistant microorganisms, and demonstrate applicability in healthcare and environmental remediation contexts.

At the same time, environmental and toxicological concerns related to nanoparticle exposure and long-term accumulation remain important considerations. Although green synthesis approaches may reduce some associated risks, further systematic studies are required to fully evaluate long-term safety, environmental fate, and biological interactions.

In summary, the biosynthesis of silver and copper nanoparticles using plant-based sources offers a sustainable alternative to conventional synthesis methods. Continued research focused on safety evaluation, standardized synthesis, and application-specific optimization will be essential for responsible development and practical implementation of green-synthesized nanoparticles.

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Not applicable.

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