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Eco-Innovations in Nanoscience: Advances in Sustainable Synthesis and Physico-Chemical Characterization of Silver Nanoparticles and their Bio Medical Applications

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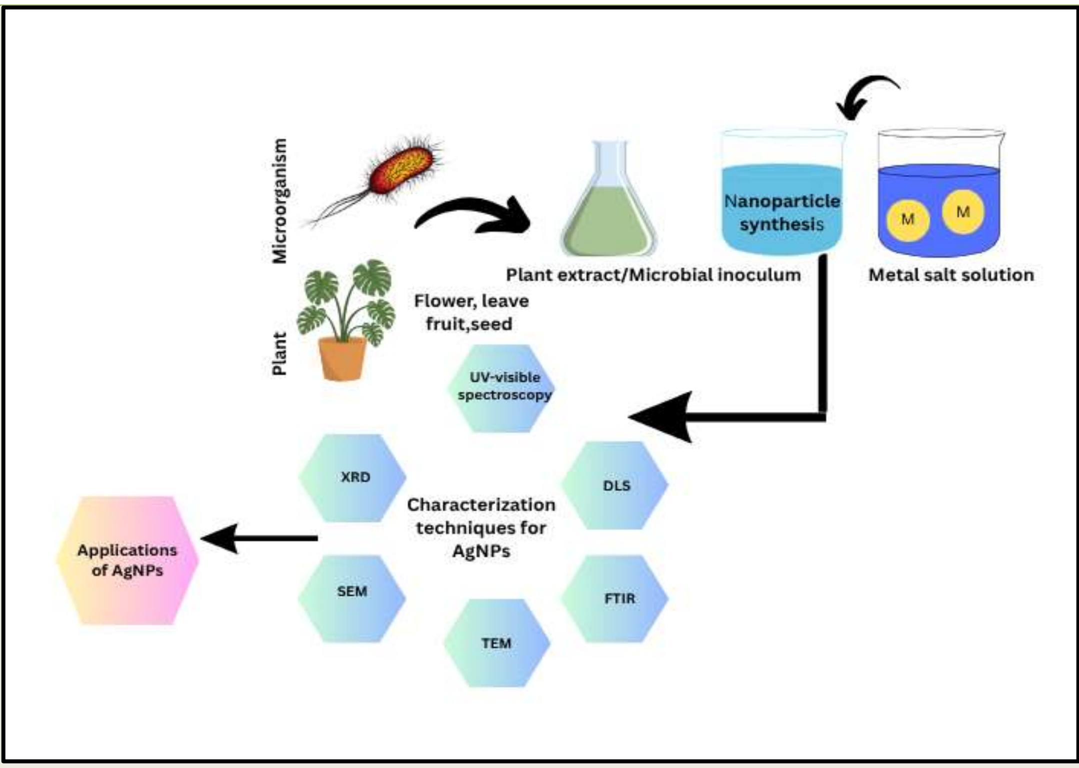
Abstract **Review Article**



Graphical abstract

An essential milestone in the realm of nanotechnology is the development of reliable and environmentally friendly processes for the production of nanoparticles. Due to their distinctive dimensions, such as size, structure, and shape, as well as their exclusive biological, physical, and chemical capabilities, nanoparticles are excellent choices for a broad range of applications across multiple sectors. Due to their special qualities, silver nanoparticles (AgNPs) have drawn plenty of attention among other nanoparticles. Many efforts have been made over the past decade to develop environmentally conscious synthesis procedures aimed at preventing harmful byproducts. AgNPs have been produced using natural sources such plants, bacteria, fungi, and biopolymers. These organic sources serve as capping and reducing agents. Green-produced AgNPs have many benefits, such as minimal toxicity, high yields, cost-effectiveness, environmental friendliness, energy efficiency, and readily accessible availability. This review emphasizes environmentally friendly methods for fabricating silver nanoparticles and the analytical techniques employed to characterize them. It also explores the potential therapeutic applications of biosynthesized silver nanoparticles derived from medicinal plants.

Keywords: Nanotechnology, Green synthesis of nanoparticles, Silver nanoparticles, Characterization techniques for AgNPs, Biomedical applications.

Highlights:

- Approaches to nanoparticles fabrication
- Ecofriendly synthesis of nanoparticles
- Plant-mediated synthesis of silver nanoparticles
- Characterization techniques for AgNPs
- Biomedical applications of AgNPs

1. INTRODUCTION

At the forefront of multidisciplinary research, nanotechnology has a profound impact on a wide range of scientific endeavors particularly in the fields of biological sciences. The atomic and molecular scale materials referred to as nanomaterials are crucial for nanotechnology, and they have a significant influence on humanity due to their ease of utilization, rapidity, cost-effectiveness, non-toxicity, and sustainability (Samuel *et al.*, 2022). Due to their distinctive size and large surface area-to-volume ratio, metallic nanoparticles play a vital role in achieving enhanced physical and biological properties across numerous fields, notably catalysis, ophthalmology, biomolecular probes, photonics, drug delivery, electronics, and display gadgets (Li *et al.*, 2011).

Silver, copper, gold, zinc, titanium, platinum, magnesium, and other metallic nanoparticles (NPs) have gained a lot of attention for their multifunctional therapeutic properties in biomedical applications (Ajitha *et al.*, 2015). A range of methods, including biological, physical, and chemical methods, are employed to fabricate metallic nanoparticles, aiming to control the morphology, size, and stability of the synthesized nanostructures. Nanoparticles can be fabricated using either a top-down approach, which involves reducing bulky materials to the nanoscale range, or a bottom-up approach, where atoms or molecules are assembled to form larger structures (Gecer *et al.*, 2022).

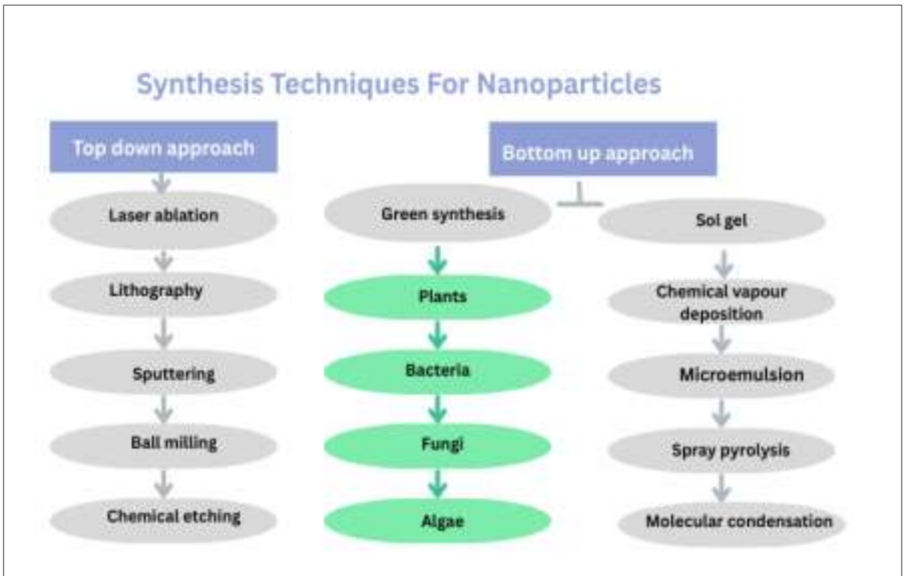


Fig 1: Techniques for synthesizing nanoparticles

The physical methodology generates nanoparticles by employing techniques such as gas-phase deposition, mechanical grinding, and laser ablation. Although it offers a more sophisticated and simpler technique in comparison to chemical and biological methods, it typically results in larger particle sizes, contamination from solvents, and uneven distribution. To prevent nanoparticles from agglomerating, an external stabilizing agent is required (Jalab *et al.*, 2021).

Chemical reduction, which makes use of both organic and inorganic reducing agents, is the most widely used technique for producing AgNPs. Several reducing agents can convert silver ions to metallic silver and cause them to assemble into clusters. These agents include elemental hydrogen, sodium citrate, ascorbate, polyol process, poly (ethylene glycol)-block polymer elemental, sodium borohydride, and the process of polyol. The nanoparticles of silver are synthesized by employing these methods (Alharbi *et al.*, 2022).

The ability to produce significant productivity of nanoparticles is a key advantage of chemical methods over their physical counterparts. The production of AgNPs often involves the use of toxic and hazardous chemicals, such as citrate, but the operations are costly. Moreover, producing AgNPs with correct size is quite difficult, and extra steps need to be done to stop particle aggregation (Zhang *et al.*, 2016).

Due to the scarcity of natural resources, the low agricultural yield of food crops, the quick changes in climate, and the enormous population expansion, worldwide food availability is currently the most difficult challenge. To satisfy the need, researchers are attempting to enhance food crop output by implementing newer inventions and technology (Roy and Pal, 2025).

Green production of metallic nanoparticles is the most intriguing manufacturing technique (Iravani *et al.*, 2014). Multiple research investigations have demonstrated that using biological synthesis techniques has distinct advantages over other traditional synthesis methods that involve rigorous requirements like inert gases, laser radiation, high temperatures and pressures, and potentially hazardous residues. Green production of nanoparticles offers other benefits such as longer half-lives of the nanomaterial, increased efficiency, and consequently lower toxicity and greater biocompatibility.

Fig 1.1: Advantages of green synthesis of nanoparticles

An eco-friendly, simple, reliable, non-toxic, and economical approach is offered by the green fabrication of nanoparticles. Utilizing bio-based reagents including fungi, yeast, bacteria, and plant extracts, together with green nanochemistry, has garnered a lot of interest in the creation of novel techniques and technologies. Improved crop protection can be achieved by using nanoparticles for site-targeted or controlled dietary intake delivery, unique agrochemical transporters, and nanofertilizers. Sustainable agriculture could undergo a new environmental revolution thanks to the promise of nanomaterials (Mohanty *et al.*, 2024).

AgNPs, or silver nanoparticles, are being investigated more and more for their prospective uses in agriculture, showing promise in the protection of crops, growth promotion, and sustainable farming methods (Anand and Bhagat, 2019). AgNPs are efficient against a variety of plant infections due to their strong antibacterial, antiviral, and antifungal properties(Franzolin *et al.*, 2022).

2. Nature-Driven Fabrication of nanoparticles

Biosynthesis is an environmentally friendly process developed from the bottom up that utilizes metal atoms to create clusters and, ultimately, nanoparticles. While chemical reduction is linked to the biosynthetic concept, the synthesis of nanoparticles is conducted using environmentally friendly materials instead of costly and hazardous chemicals (Sharma *et al.*, 2019).

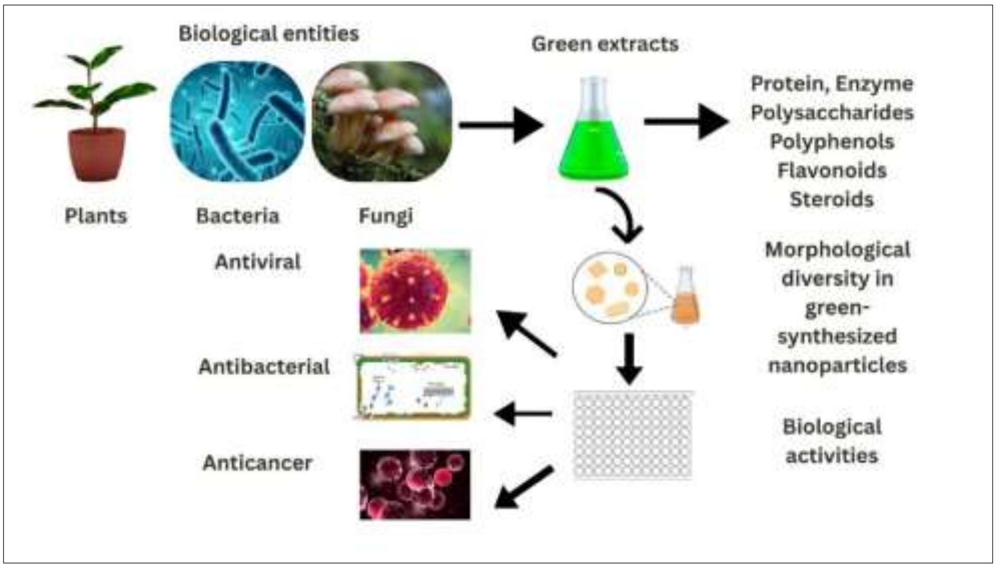


Fig 2: Nature driven synthesis of nanoparticles

Biosynthesis encompasses cells, plants, microorganisms, and biological components and can even take place in vivo. It streamlines preparation, minimizes toxicity, and improves biocompatibility. Biological imaging, antibiotic degradation, and the treatment of various diseases, including tuberculosis and myocarditis associated with cadmium exposure, can all be addressed with biosynthesized nanoparticles (Zhang and Liu, 2023).

2.1 Bacterial Based synthesis of nanoparticles

Bacteria can generate metal nanoparticles (NPs) both extracellularly and intracellularly. Research has shown that extracellular synthesis is more efficient and facilitates simpler NP extraction. Due to their enhanced oxidation resistance, biosynthetic metal nanoparticles can be utilized in a wide range of applications (Tsekhmistrenko *et al.*, 2020). The process of creating NPs extracellularly involves cultivating microorganisms in an appropriate medium. After centrifuging the broth containing the microbial cells, the microbial enzyme-containing supernatant creates NPs. In a different container, the metal ions and the reductase enzyme-containing supernatant are allowed to react. NPs are produced when metal ions undergo bio reduction in a cell-free supernatant (Koul *et al.*, 2021). In intracellular manufacture, NPs are synthesized via the cellular process of microbial cells. The microbial cultures are kept in suitable liquid media, and the biomass is separated into pellets by centrifugation after being cleaned with sterile distilled water (Fernández-Llamosas *et al.*, 2017). After that, an aqueous metal solution is added to the microbial biomass and allowed to react. A particular chromatic change is then noticed after the resultant solution containing the metals and microbial biomass has been cultured under the specified incubation conditions. The development of NPs is indicated by the emergence of a certain hue (Waghmare *et al.*, 2015).

In order to synthesize AgNPs, the most frequently investigated bacterial species are *Escherichia coli*, *Lactobacillus sp, Bacillus cereus, Acinetobacter sp*, *Pseudomonas sp, Corynebacterium sp*, and *Klebsiella pneumonia* (Koul *et al*., 2021). For the bioremediation of organic dyes, the biosynthesized TiO_2NPs demonstrated outstanding photo catalytic activity against methyl orange (MO) dye, degrading 99% of MOdye. A Gram-negative proteobacteria called *Halomonas elongata* (strain IBRC-M 10214) was effectively used for the environmentally friendly synthesis of ZnONPs and TiO_2NPs (Taran *et al.*, 2017).

2.2 Fungi mediated synthesis of nanoparticles

Due to their improved growth control and range of metabolites, which include peptides, enzymes, polysaccharides, protein, and various other macromolecules, fungi have emerged as useful instruments for the production of nanoparticles when compared to other biological systems (Anjum *et al.*, 2023). Enzymes and other physiologically active substances can facilitate the intracellular and extracellular production of nanoparticles by fungus.

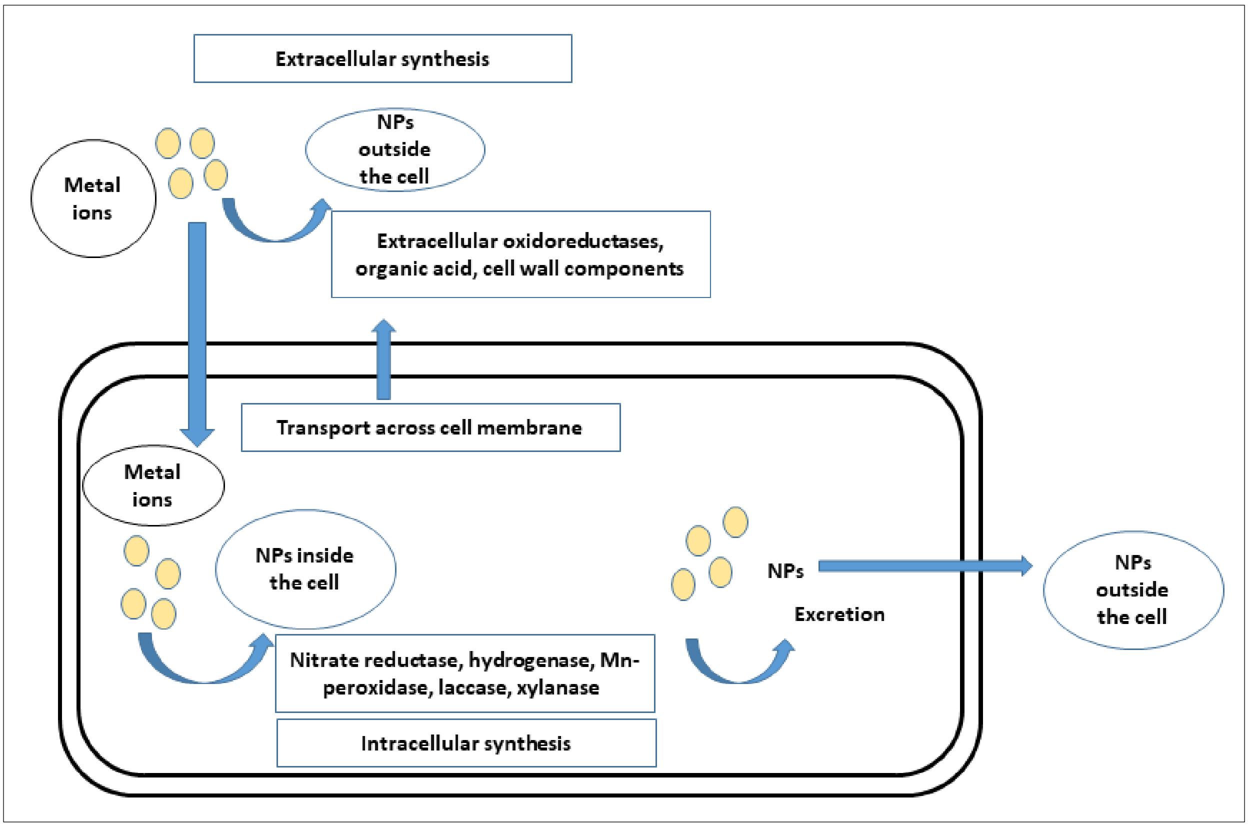


Fig 2.1: Schematic diagram of fungi mediated synthesis of nanoparticles

Phoma sp. mycelial biomass was employed to produce gold nanospheres (10–100 nm) having antibacterial and antifungal qualities. Cubic AuNPs with potent antioxidant, cytotoxic, and antibacterial properties were produced using an extract from the fruit body of *Morchella esculenta* (Acay, 2021). *Candida albicans* and *Aspergillus flavus* fluids were used to mycosynthesize selenium nanospheres, which demonstrated strong antifungal effectiveness by inhibiting fungal growth at lower nanoparticle concentrations than antifungal medications (Loshchinina *et al.*, 2022). In order to identify the most promising fungal cultures for AgNP biofabrication, several researchers have screened them. AgNPs were created from extracts of the fruit bodies of *Pleurotus florida* utilizing a variety of electromagnetic radiations, including microwaves, visible light, and ultraviolet light (Kaur *et al.*, 2020). The extracts of *Trichoderma longibrachiatum* xylanases and *Aspergillus niger* were used to create silver nanospheres, which demonstrated thrombolytic, antioxidant, antifungal, antibacterial, and dye-degrading properties (Elegbede *et al.*, 2018). Several studies have demonstrated that mycosynthesized silver nanoparticles (AgNPs) possess a variety of biological activities and antioxidant, antifungal, antibacterial, anticancer, and larvicidal characteristics. For instance, *Flammulina velutipes* were used to create silver nanospheres, which shown good biocompatibility against human red blood cells and featured antibacterial, fungicidal, anti-Alzheimer, anticancer, antioxidant, and anti-diabetic properties (Faisal *et al.*, 2020).

2.3 Plant mediated synthesis of nanoparticles

Plant biotechnology and nanotechnology are connected via the green chemistry method of phyto-fabrication, which is the formation of Nanoparticles using plants or plant extracts as a precursor (Rani *et al.*, 2023). Using plant extracts as stabilizers and reductants to create MNPs offers the benefits of being inexpensive, sustainable, eco-friendly, and simple to utilize. The existence of bioactive compounds found in plants, such as alkaloids, quinines, phenols, tannins, terpenoids or flavonoids, which not only have antioxidant and antibacterial properties but also stabilize nanoparticles and reduce metal salts, is primarily what makes this technique feasible (Bao *et al.*, 2021).

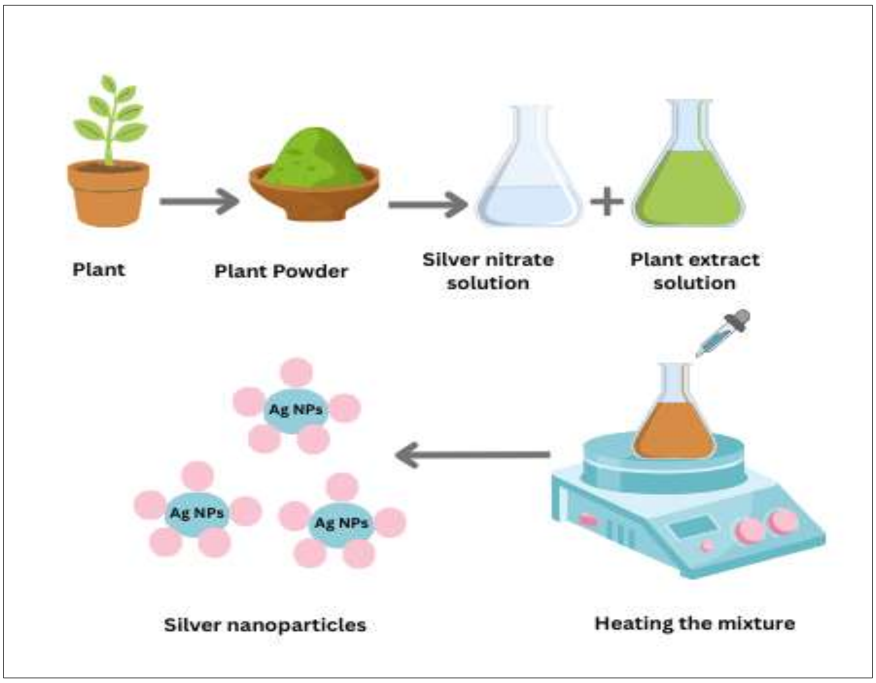


Fig 2.2: Schematic representation of plant mediated synthesis of nanoparticles

Due to its many benefits, including being quicker, easier to use, and more economical, the plant-mediated synthesis method of MNPs has attracted a lot of interest from researchers around the globe. Furthermore, in addition to their exceptional biocompatibility, biodegradability, affordability, and environmental friendliness, plant extracts provide MNPs with a stable protective covering that prevents them from aggregating (Chung *et al.*, 2016). *Holopetelea integrifolia* leaf extract's antibacterial, anti-inflammatory, antidiabetic, and antioxidant properties were investigated, as well as the antibacterial, anticancer, and antioxidant properties of formulated gold nanoparticles from *Halymenia dilatata* and conjugated gold nanoparticles from *Nerium oleander* that were tested against MCR-7 cell lines (Muddapur *et al.*, 2022).

3. Plant mediated synthesis of silver nanoparticles

The production of Ag/Ag_2O NPs from plant extracts in an aqueous medium proves advantageous for biological applications, as the final particles are often directly usable. Plant extracts are also frequently used in the environmentally friendly synthesis of metals and metal oxide nanoparticles (NPs) because they contain phytochemicals such as organic acids, flavonoids, terpenoids, phenolic compounds, and alkaloid substances that function as both a covering agent and a bio-reducing agent (Belaiche *et al.*, 2021).

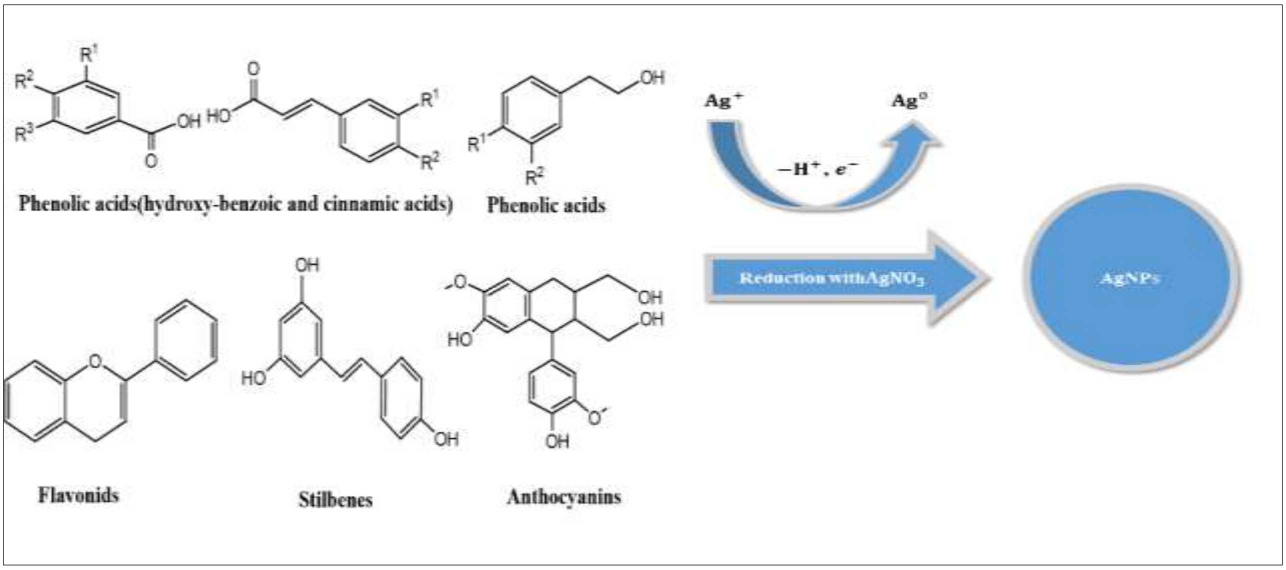


Fig 3: Plant mediated fabrication of silver nanoparticles

In the past, Shikakai (Acacia concinna) and Reetha (*Sapindus mukorossi*) were used as detergent and shampoo. The aqueous plant extracts of Reetha and Shikakai were used as potential biosources for reducing and stabilizing agents in the environmentally friendly green production of silver nanoparticles. X-ray diffraction (XRD), transmission electron microscopy (TEM), and UV-visible spectroscopy were employed to examine the biosynthesized silver nanoparticles. Moreover, the biosynthesized silver nanoparticles were utilized as SERS-active substrates for the rapid identification of pathogenic bacteria, such as Mycobacterium tuberculosis, which is known to be resistant to the majority of widely used pharmaceuticals (Sur *et al.*, 2018).

A flower extract from *Ferulago macrocarpa* was used to phytosynthesize silver nanoparticles (SNPs) from a silver nitrate solution. The SNPs were characterized using FT-IR, SEM, EDX, XRF, XRD, and UV-visible analysis. The SNPs showed effectiveness against *Candida albicans*, *Klebsiella pneumonia*, *Escherichia coli*, *Bacillus cereus*, and *Staphylococcus aureus*. At up to 250 µg/mL, they did not, however, exhibit toxicity to healthy peripheral blood mononuclear cells. The toxicity of the SNPs is likely decreased by the extract biomolecules' coating on their surface. As a result, bacterial infections may be prevented and treated with the synthetic SNPs (Azarbani and Shiravand, 2020).

The economically significant malvaceous vegetable crop *Abelmoschus esculentus* (L.) Moench, commonly referred to as okra, is high in minerals, nutrients, and vitamins and is used in a variety of culinary applications. AgNPs were synthesized in this study using extracts from *A. esculentus* flowers as a moderating agent. The synthesis of AgNPs was validated through several characterizations. TEM revealed that the produced material had a mostly spherical, less aggregated morphological nature, with an average size of less than 19 nm. All gram-negative and gram-positive microbial pathogens were susceptible to the antibacterial activity of the NPs. The produced nanoparticles were examined under a microscope to investigate cytotoxicity and apoptosis; necrosis, hypertrophy, pycnotic nuclei, and nuclear disintegration were found (Devanesan and AlSalhi, 2021).

Aerva lanata (Al) flower extracts from the family Amaranthaceae were used to create silver nanoparticles (AgNPs) in an environmentally friendly manner. Silver nanoparticles with a poly-dispersed indexed value of 0.419 and mean size of 7.6 nm in the 5-15 nm range were observed in dynamic light scattering (DLS). A value of -18.7 mV was found for the zeta potential that contributes to the stability of silver nanoparticles. The presence of the produced AgNPs, which have an average size range of 7 ± 3 nm, was verified by energy dispersive X-ray (EDX) analysis and Transmission electron microscope (TEM). Silver nanoparticles at a concentration of 100 µg/ml demonstrated antioxidant capability in the 2,2'-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging experiment. UV-Vis spectroscopy was used to measure the decolorization of the dyes in the presence of sunshine in order to assess the photocatalytic capability of silver nanoparticles. The findings imply that *A. lanata* floral extract-derived biosynthesized silver nanoparticles (Al-AgNPs) possess broad-spectrum antibacterial, antioxidant, and catalytic properties that could be beneficial in a range of industrial and therapeutic applications (Palithya *et al.*, 2022).

The exceptional catalytic qualities of silver nanoparticles (SNP) in the degradation of the dye process have drawn a lot of interest. A quick and inexpensive method for producing silver nanoparticles from $AgNO_3$ involves employing the aqueous extract of *Thunbergia grandiflora* flowers and their catalytic breakdown of the Congo red (CR) dye. At 430 nm, the UV-visible spectra showed a distinctive peak. Spherical nanoparticles were revealed via SEM examination. At 3.1 keV, the EDX spectrum showed a silver peak. XRD analysis revealed a 38.31° peak. Excellent catalytic efficacy was demonstrated by the nanoparticles in the reduction of CR dye. (Varadavenkatesan *et al.*, 2020).

An aqueous root extract of *Premena integrifolia* (PE-AgNPs) has been used to create green synthesis of silver nanoparticles that is effective, repeatable and environmentally bengin. Several methods were used to characterize the produced nanoparticles in order to ascertain their morphology, stability, and formation. Using the MTT assay, Hoechst and AO/EtBr staining, ROS detection, clonogenic, and wound healing assays, the cytotoxic potential of PE-AgNPs was examined. In every test, PE-AgNPs were shown to be highly toxic to Hep G2 cell lines. Pseudomonas aeruginosa was more vulnerable to PE-AgNPs than Staphylococcus aureus and E.coli, according to disc diffusion assay (Singh *et al.*, 2023).

Phytosynthesis is a straightforward, repeatable, and efficient way to create extremely stable metal nanoparticles. As a sustainable, economical, and non-hazardous stabilizing agent, *Zephyranthes candida* (*Z.candida)* flower extract was used to create Silver nanoparticles. X-ray diffraction (XRD) examination showed that Ag NPs have a face-centered cubic structure. The creations of Ag NPs were further validated by surface plasmon resonance (SPR) at the greatest absorbance (λmax) of 418 nm based on the UV-Vis spectral analysis. Anti-inflammatory, anti-diabetic, antioxidant, and anticancer biological studies validate the bioactivity of the produced *Zephyranthes Candida*-mediated Ag NPs (Kaliammal *et al.*, 2021).

Using an aqueous leaf extract from *Phoenix dactylifera L.*, the eco-friendly synthesis of Ag/Ag_2O nanoparticles was successfully accomplished. The procedure is straightforward, quick, inexpensive, safe for the environment, and doesn't call for any hazardous chemicals or organic solvents. The prepared Ag/Ag_2O NPs exhibited a spherical shape and had an average size between 28 and 39 nanometres. The produced Ag/Ag_2O NPs exhibit superior photocatalytic activity for the breakdown of azo dyes. The produced Ag/Ag_2O NPs photocatalyst aids in wastewater treatment (color degradation) in textiles, paints, plastics, medications, and cosmetics (Laouini *et al.*, 2021).

Table 1: Various plants species used for the fabrication of silver nanoparticles their activities and characterizations

Plants	Parts	Size	Characterization	Activities	Reference
Ruta graveolens	Leaves	40-45 nm	Fourier transform infrared spectroscopy SEM	Anticancer Antibacterial Insecticidal	(Ghramh *et al.*, 2020)
Aaronsohnia factorovskyi	Stem, Leave, Flower	104-140nm	UV-Visible, FE-SEM GC-MS, FT-IR	Antibacterial, Antifungal	(Al-Otibi *et al.*, 2020)
Eucalyptus camaldulensis	leaves	16-28nm	UV-Vis, XRD, Zeta, EDX, SEM, FTIR, DLS	Antioxidant	(Alghoraibi *et al.*, 2020)
Terminalia arjuna	leaves	10-50nm	Ultra-violet, FT-IR, TEM, XRD, FE-SEM	Catalytic removal of Organic dyes	(Raj *et al.*, 2020)
Litchi chinensis	leaves	5-15nm	UV-Vis, TEM, FTIR	Sporocidal and Bactericidal	(Tehri *et al.*, 2020)
Corn cobs	Xylan	55.3nm	UV–Vis, EDS, DLS, AFM, SEM, FTIR, Raman spectroscopy, flow cytometery	Anti-parasitic activity, cytotoxicity	(Brito *et al.*, 2020)
Rosa santana	Petals	6.5-25.24nm	UV-Vis, FTIR. TEM, XRD	Antibacterial, Cytotoxicity	(Jahan *et al.*, 2019)
Acacia nilotica	Stalk	27-50nm	UV-Vis, DLS, XPS, XRD, TEM, SEM, FTIR	Antibacterial, Antifungal, Degradation of dyes	(Shah *et al.*, 2020)
Murraya koenigii	leaves	42 nm	UV-VIS, SEM, FT-IR	Antibacterial, Cytotoxicity	(Sankarganesh *et al.*, 2021)

3.1 Characterization techniques for green synthesized silver nanoparticles

The activities, biodistribution, safety, and efficacy of nanoparticles depend upon their physicochemical characteristics. Consequently, AgNPs must be characterized employing a range of analytical techniques, including UV-visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffractometry (XRD), dynamic light scattering (DLS),scanning electron microscopy (SEM), and transmission electron microscope (Alharbi *et al.*, 2022).

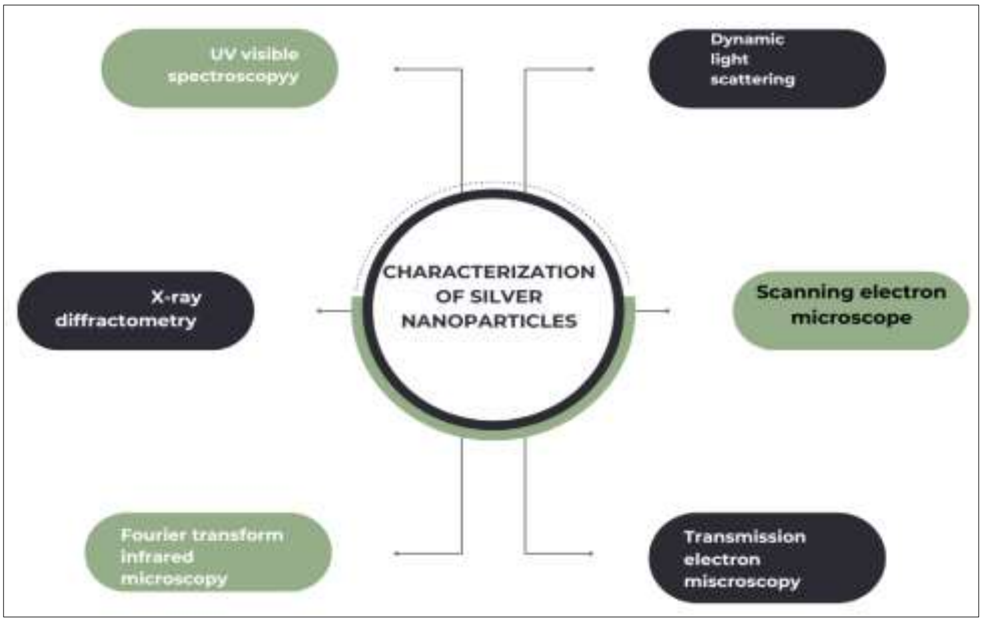


Fig 3.1: Characterization technique for silver nanoparticles

- **UV-visible spectroscopy**

UV-Vis spectroscopy is a useful tool for characterizing synthesized AgNPs. Nanoparticle presence is often indicated by wavelengths between 400 and 800 nm. The intensity and location of SPR peak which appears at wavelength between 380 and 450 nm, can be used to demonstrate the quality of the synthesized nanoparticles. A large size of aggregated AgNPs is indicated by a broad peak at a high wavelength, whereas, a low wavelength with a narrow peak indicates that the nanoparticles are small. The creation of colloidal AgNPs was confirmed by the UV-visible absorption spectra's strong peak at 410 nm (Habeeb Rahuman *et al.*, 2022).

- **X-ray diffractometry:**

The analytical method known as X-ray diffraction (XRD) is widely used technique for evaluating crystal and molecular structures. It may evaluate particle size, isomorphous substitution, crystallinity, and the qualitative resolution of various molecules. This technique is also helpful for figuring out purity because it makes it clear if a material is pure or has impurities. Bragg's law serves as the foundation for XRD, which assists in determining AgNPs' Bragg reflection. The XRD analysis demonstrates that the synthesized silver nanoparticles exhibit distinct diffraction peaks at (111), (200), (220), (311), (331), and (222) (Mashwani *et al.*, 2015). The sharpness of the diffraction peaks (111), (200), and (220) suggests the creation of nano-sized particles, but the peaks themselves represent a face-centered cubic structure (Alaqad and Saleh, 2016).

- **Fourier-transform infrared spectroscopy:**

The functional groups accountable for the creation of AgNPs can be identified via FTIR spectroscopy. In FTIR spectroscopy analysis, the absorption spectrum profile displays unique peaks that signify significant quantities of specific chemical bond types. Additionally, different functional groups, including amines, ketones, and alkanes, absorb infrared radiation at different wavelengths, enabling the identification of biomolecules (Palithya *et al.*, 2022) . The functional groups that contribute to the surface coating and efficient stabilization of the generated nanoparticles can be identified by comparing the FTIR spectra of the biosynthesized AgNPs with those of a medicinal plant extract (Akintelu *et al.*, 2020).

- **Dynamic light scattering**

Nanoparticle size distribution, surface charge, and size can all be investigated using DLS. The measurement provided the polydispersity index (PDI), which defined the width of the particle size distribution, the average hydrodynamic diameter of the particle, and the peak values in the hydrodynamic diameter distribution. The PDI scale has a range of 0 and 1, where 1 indicates polydispersity and 0 indicates monodispersity. At 25°C, all measurements were performed in triplicate and required a one-minute temperature equilibration period (Elamawi *et al.*, 2018). Synthetic AgNPs derived from *Phoenix dactylifera* seeds appear to be a polydisperse mixture of particle having a hydrodynamic diameter of 203 nm (Khader *et al.*, 2022).

- **Scanning electron microscope**

The surface imaging method known as SEM is one of the many electron microscopy techniques that can resolve varied size distributions, nanomaterial forms, particle sizes, and surface morphology of synthesized particles at the micro- and nanoscales. Although it is unable to clarify the internal structure, the present high-resolution SEM can distinguish the shape of nanoparticles below the 10 nm level and provide useful information about the level of particle aggregation (Patil and Chougale, 2021). With a combination of SEM and EDX, elemental analysis and morphological evaluation of the silver nanoparticles could be carried out (Habeeb Rahuman *et al.*, 2022).

- **Transmission electron microscope:**

TEM is a useful, widely applied, and significant method for characterizing nanomaterials, yielding quantitative measurements of size distribution, morphology, and particle and/or grain size. Triangular, hexagonal, dodecahedral, and spherical Ag and Au nanoparticles with an average size of 13–14 nm were seen in TEM images following the bioreduction of Ag and Au ions using leaf extract from *Hibiscus rosa-sinensis* (Philip, 2010). The TEM image examination at different magnifications revealed that the bio-synthesized *Aerva lanta*-mediated silver nanoparticles were spherical, poly-dispersed, and ranged in size from 2 to 10 nm, with an average of 7 ± 3 nm. (Palithya *et al.*, 2022). Compared to SEM, TEM offers two benefits; the capacity for more analytical experiments and improved spatial resolution. The disadvantages include the narrow sample section and high vacuum requirements (Lin *et al.*, 2014).

3.2 Biomedical Applications of green synthesized silver nanoparticles:

AgNPs have been used for decades to control and treat a variety of illnesses because of their well-known and effective biocidal effect on bacteria (Oei *et al.*, 2012). There is a lot of interest in the therapeutically improved personalized healthcare practice among the current biological potential of AgNPs. AgNPs demonstrated their true qualities and remarkable potential for the creation of new antimicrobial agents, drug delivery systems, platforms for detection and diagnosis, coatings for biomaterials and medical devices, materials for tissue regeneration and restoration, intricate healthcare condition techniques, and therapeutic substitutes that work better (Burdușel *et al.*, 2018).

AgNPs are believed to possess antiviral properties and to serve as a potent and effective pharmacological agent. In experiments conducted against CHIKV, biologically synthesized silver nanoparticles derived from *Andrographis paniculata*, *Phyllanthus niruri*, and *Tinospora codifolia* demonstrated encouraging antiviral properties (Sharma *et al.*, 2019). According to these findings, it is feasible to plant derived AgNPs as antiviral medications, and they may provide alternate treatment for viral diseases for which there is presently no specific antiviral vaccination. The viral replication mechanism is caused by AgNPs' contact with the viral core and virion surface. After attaching themselves to the virus's glycoprotein, AgNPs stick to the genome and cellular components, stopping the virus's ability to replicate (Khandelwal *et al.*, 2014).

Cancer is a complex, multidimensional disease characterized by the uncontrolled growth and spread of abnormal cells caused by a combination of internal, external, environmental, and genetic factors.(Siegel *et al.*, 2015). AgNPs have been proven in numerous in vitro and in vivo investigations to potentially limit the viability and development of cancer cells. AgNPs have the potential to trigger necrosis and apoptosis by altering the ultrastructure of cancer cells, producing ROS, and damaging DNA. By changing critical signaling pathways including the hypoxia-inducible factor (HIF) pathway and up-or down-regulating the expression of key genes like p53, AgNPs may cause apoptosis. Cell cycle arrest may also occur in cancer cells treated with AgNPs (Yin *et al.*, 2022).

AgNPs are used in water treatment disinfectants as antimicrobials. Furthermore, the increased ion release and increased catalytic activity brought about by AgNPs' huge surface area per mass have drawn a lot of attention to their applications in the textile industry. AgNPs are incorporated into the fabric using two main techniques: (1) introducing pre-formed nanoparticles into the substrates, and (2) putting the substrates in a silver salt solution and treating them with reducing agents to turn the silver salts into AgNPs (Jia *et al.*, 2020). Excellent antibacterial activity and a uniform dispersion of AgNPs are demonstrated by a silver nanocoated cloth (El-Shishtawy *et al.*, 2011).

Future perspectives and conclusion of AgNPs:

The creation of metallic nanoparticles by biological means has attracted a lot of interest lately and has become a prominent area of study. Bacteria, fungus, yeast, micro-algae, seaweeds, and plant parts are among the many biological materials that have demonstrated the ability to synthesize various metallic and metal oxide nanoparticles, including Ag, Au, Pd, Pt, Cu, ZnO, CuO, and TiO_2. The nanostructure of silver nanoparticles (AgNPs) is being thoroughly investigated for novel and improved biological uses. Alternatives for drug administration, wound dressing, tissue scaffolding, and protective coating applications include AgNP-based nanosystems and nanomaterials. Furthermore, by inhibiting angiogenesis within the lesion, AgNPs may stop the invasion and migration of cancer cells. Cytotoxicity of silver nanoparticles, however, might limit their application in medicine. It is generally believed that sufficient surface functionalization will improve AgNP compatibility. Nowadays, the primary issues with AgNP applications are their cytotoxicity and aggregation. Finally, research focused on enhancing our understanding of the cytotoxic effects of silver nanoparticles (AgNPs) on the environment, by advancing technological boundaries, may enhance the future prospects of AgNPs.

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