Green Synthesis and Characterization of Noble Metal Nanoparticles (Ag, Au,Pt) Using Plant Extracts: Antibacterial and Antifungal Applications

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Abstract

Metallic nanoparticles (MNPs) exhibit unique physicochemical properties that make them highly valuable across a wide range of applications, including mechanical, electrical, thermal, optical, and biological domains. Extensive research has been dedicated to uncovering the advantages of MNPs, which stem from their nanoscale size and associated characteristics. The growing demand for these nanoparticles has spurred interest in developing synthesis methods that are efficient, cost-effective, rapid, and environmentally sustainable. Among the various categories of MNPs, noble metal nanoparticles (NMNPs), particularly those composed of silver (Ag), gold (Au), and platinum (Pt), have gained significant attention due to their superior properties and broad applications. For instance, microbial contamination remains a persistent issue in industries such as food production, medical devices, and water treatment. To mitigate these challenges, nanoscale materials, especially NMNPs, have been explored for their innovative antimicrobial capabilities. This review highlights green synthesis approaches for NMNPs, including AgNPs, AuNPs, and PtNPs, using plant extracts and examines their antibacterial effectiveness.

Keywords:Green Synthesis, Noble Metal Nanoparticles, Silver Nanoparticles, Gold Nanoparticles, Platinum Nanoparticles, Antibacterial Activity, Antifungal Activity.

Introduction

Nanoparticles (NPs) have become integral to advancements in science and industry due to their unique physicochemical properties that differ significantly from their bulk counterparts [1]. These nanoscale materials have garnered attention for their diverse applications across biomedicine, environmental science, and advanced manufacturing. Among the various types of nanoparticles, metal nanoparticles (MNPs) are particularly noteworthy because of their exceptional chemical reactivity, optical properties, and surface plasmon resonance effects [2]. The study of MNPs began in the 19th century when Michael Faraday explored the behaviour of colloidal gold, and Gustav Mie later provided theoretical explanations for their optical phenomena [3]. However, their use extends back to medieval times, where MNPs were employed to produce the vibrant colors in stained glass. Today, noble metal nanoparticles (NMNPs)—such as those derived from silver (Ag), gold (Au), and platinum (Pt)—are of great interest due to their superior chemical stability, biocompatibility, and multifunctionality. Silver nanoparticles

(AgNPs) are recognized for their potent antimicrobial properties, making them valuable in healthcare, food preservation, and consumer products [4]. Gold nanoparticles (AuNPs) are widely used in biomedical applications, including diagnostics, drug delivery, and imaging [5]. Meanwhile, platinum nanoparticles (PtNPs), though less extensively studied, are gaining attention for their potential in cancer therapy, biosensing, and catalytic processes [6]. These applications highlight the pivotal role of NMNPs in addressing pressing challenges in healthcare and environmental sustainability. Despite their promise, the synthesis of NMNPs faces significant challenges. Conventional methods such as chemical reduction, photochemical techniques, and electrochemical processes often involve high energy consumption, hazardous chemicals, and limited scalability [7]. These issues underscore the need for greener and more sustainable approaches. The global movement toward environmentally responsible practices, influenced by milestones like Rachel Carson's *Silent Spring* (1962), has driven the adoption of eco-friendly technologies. In this context, the *Twelve Principles of Green Chemistry*, introduced by John C. Warner and Paul Anastas in 1998, serve as a foundation for designing safer, more sustainable chemical processes. These principles have inspired the development of innovative methods that minimize toxicity, energy usage, and waste generation. One such method is the plant-based synthesis of nanoparticles, which has gained traction as an efficient, eco-friendly, and straightforward technique [8].

Plant-mediated synthesis utilizes plant extracts as natural reducing and stabilizing agents to transform metallic salts into nanoparticles. Unlike microbial-based synthesis, which requires labor-intensive cultivation and carries risks of contamination, plant-based approaches are simpler and safer, aligning closely with green chemistry principles. This method also leverages a wide variety of plant materials, such as flowers, fruits, peels, seeds, roots, leaves, and latex, to achieve effective nanoparticle biosynthesis [9]. Over the last decade, plant-mediated synthesis has been extensively explored for producing AuNPs, AgNPs and PtNPs. These nanoparticles are highly valued for their biocompatibility, reduced toxicity, and versatility in applications ranging from medicine to environmental science. Additionally, their synthesis via plant-based methods offers a sustainable alternative to conventional techniques, addressing critical concerns about environmental safety and human health [10-12].

This study aims to explore the potential of plant-mediated synthesis in producing MNPs, focusing particularly on AgNPs, AuNPs and PtNPs and their antimicrobial activities. By investigating the effectiveness of various plant extracts in facilitating nanoparticle formation, the research seeks to contribute to the advancement of green nanotechnology and its alignment with the principles of green chemistry.

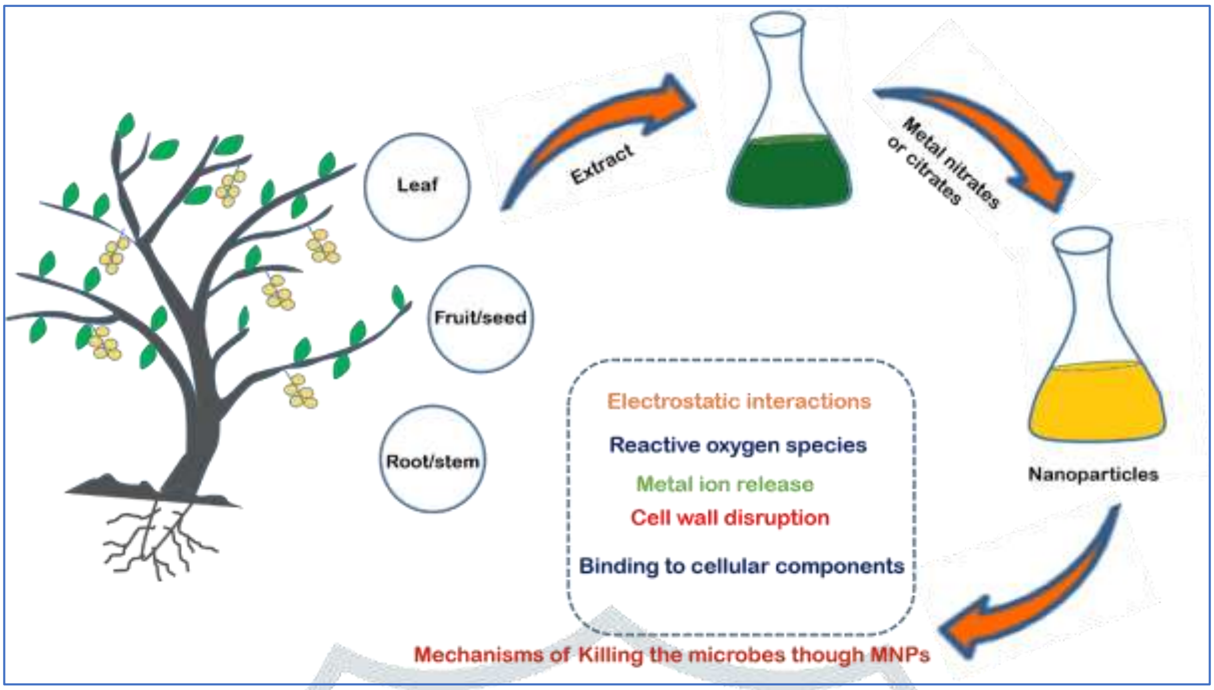

Fig 1: *A visual depiction of the environmentally friendly synthesis of metallic nanoparticles utilizing plant materials, bacteria, and fungi is presented. Additionally, the different mechanisms through which bacterial cells undergo death are also depicted.*

Plant based Synthesis and mechanism of Ag, Au and Pt nanoparticles

Nanomaterials with unique properties are essential for a variety of applications, including sensing, catalysis, electronics, photonics, and biomedicine. Traditionally, their synthesis is categorized into two primary approaches: top-down, where bulk materials are reduced to nanoscale dimensions, and bottom-up, where materials are assembled atom by atom or molecule by molecule [13]. However, these conventional methods often involve the use of hazardous chemicals, organic solvents, and stabilizing agents, raising significant concerns about their toxicity and environmental impact [14]. To address these challenges, researchers have shifted focus toward safer and more sustainable alternatives. Green synthesis techniques, which leverage natural resources such as plant extracts, microorganisms, and marine algae, have emerged as promising solutions. These methods are particularly valued for synthesizing nanoparticles intended for medical applications [15]. One of the most notable developments in nanotechnology is the use of plants to synthesize noble metal nanoparticles, such as silver (Ag), gold (Au), and platinum (Pt). This approach has gained popularity due to its eco-friendliness, safety, cost-effectiveness, and scalability [16]. Compared to conventional physical and chemical methods, plant-based synthesis is not only simpler but also reduces environmental harm. The pioneering study on this topic, conducted in 2003, utilized alfalfa (Medicago sativa) to synthesize nanoparticles, marking a significant milestone in green nanotechnology [17]. Various plant parts, including roots, bark, stems, leaves, fruits, seeds, peels, flowers, and calluses, have since been used to produce nanoparticles. The underlying mechanism involves the bio-reduction of metal ions by compounds present in plant extracts. Proteins and other biomolecules in the extracts bind to the metal ions through electrostatic interactions, facilitating their reduction. This process modifies the metal ions' structure and leads to the formation of metal nuclei, which grow as additional metal ions are reduced and deposited. The efficiency of this reduction process is primarily attributed to phytochemicals such as ketones, terpenoids, amides, flavones, carboxylic acids, and aldehydes [18]. Water-soluble phytochemicals, including organic acids, quinones, and flavones, are particularly effective in rapidly reducing metal ions, especially silver [19]. Moreover, plant-derived reducing agents often double as capping and stabilizing agents, eliminating the need for external stabilizers. This dual functionality makes the process even more efficient and environmentally sustainable. It is also worth noting that the nature and composition of the plant extract significantly influence the characteristics of the resulting nanoparticles, such as their size, shape, and stability [20, 21].

Synthesis of metal nanoparticles

The typical procedure for plant-mediated MNPs synthesis involves several steps: collecting plant materials from various parts of the plant, washing them with detergents, and rinsing thoroughly with double distilled water 2-3 times. The washed plant materials should be slightly air-dried. Next, the materials are weighed and boiled in 100 ml of deionized distilled water at a temperature of about 60 to 80°C for 10 to 15 minutes. The resulting solution is then filtered through nylon mesh cloth and stored at 4°C for nanoparticle synthesis. After that, the filtrate is mixed with an aqueous solution of Metal Nitrates or Metal Acetates at a final concentration of 1 mM and kept at room temperature. Color changes in the mixture soon indicate the formation of metal nanoparticles due to the reaction between the plant extract and metal ions. The formation of metal nanoparticles can also be confirmed using a UV-visible spectrophotometer, cryal size can be confirmed by XRD and morphological studies can be done through TEM or SEM.

Plant Extracts Used recently for Silver Nanoparticles (AgNPs) Preparation

The synthesis of silver nanoparticles (AgNPs) using plant extracts leverages the unique phytochemical properties of each plant, which act as natural reducing and stabilizing agents.

For instance, using the stem extracts of Callicarpa maingayi, Shameli et al. demonstrated that aldehyde groups within the extract effectively reduced Ag^+ ions to metallic silver, resulting in nanoparticle formation [22]. Similarly, Jeyaraj et al. employed leaf extracts of Podophyllum hexandrum to produce spherical AgNPs with an average size of 14 nm [23]. Expanding on this, Acalypha indica leaf extract was utilized by Krishnaraj et al. for rapid synthesis, yielding nanoparticles sized between 15 and 50 nm within just 30 minutes [24]. Additionally, orange peel (Citrus sinensis), a common food industry by-product, served as a reductive agent for bio-mimetic nanoparticle synthesis. TEM analysis revealed well-dispersed particles predominantly measuring 6 nm, with sizes ranging from 3 to 12 nm [25]. Tea extract, known for its rich bioactive composition, was used as a capping agent in another study. This method produced silver nanoparticles ranging from 20 to 90 nm, with reaction efficiency and nanoparticle formation rate significantly influenced by temperature and tea extract concentration [26]. A similar approach was taken with Tribulus terrestris dried fruit body extract, which yielded spherical nanoparticles between 16 and 28 nm. These particles demonstrated strong antibacterial activity, particularly against multi-drug resistant bacteria [27].

Cymbopogon citratus (lemongrass), a widely cultivated herb, was also used for synthesizing nanoparticles ranging from 16 to 28 nm. The resulting nanoparticles exhibited notable antibacterial properties, highlighting their potential against resistant pathogens [28]. Meanwhile, Ziziphora tenuior leaves facilitated the synthesis of uniform spherical nanoparticles sized between 8 and 40 nm. FTIR spectroscopy identified functional groups such as amines, hydroxyls, and carbonyls, which contributed to nanoparticle stabilization [29]. A unique thermal method involving natural rubber latex from Hevea brasiliensis and aqueous silver nitrate solutions produced colloidal nanoparticles. These nanoparticles, sized between 2 and 10 nm, displayed a spherical morphology and a face-centered cubic crystalline structure [30]. Similarly, Ahmed et al. employed aqueous extracts of Azadirachta indica leaves, focusing on growth kinetics to synthesize nanoparticles with 34 nm [31]. In a different approach, Ficus carica leaf extract was used to synthesize nanoparticles through irradiation. After three hours of incubation at 37 °C with a 5 mM silver nitrate solution, well-formed nanoparticles were observed [32]. Further emphasizing rapid methods, Alternanthera dentata extract enabled the synthesis of spherical nanoparticles measuring 50 to 100 nm, demonstrating the versatility of plant-based reductants [33].

Different plant parts that contain various biological compounds facilitating the reduction of silver ions to silver nanoparticles are outlined below.

1. Neem (Azadirachta indica): The extract from neem leaves, rich in flavonoids and terpenoids, facilitates the reduction of silver ions to AgNPs and provides stability to the nanoparticles [34].

2. Aloe Vera (Aloe vera): Aloe vera gel or leaf extract, containing polysaccharides, amino acids, and vitamins, acts as an effective reducing agent and stabilizer [35].

3. Tulsi (Ocimum tenuiflorum): The aqueous extract of tulsi leaves, abundant in phenolic compounds and antioxidants, is widely used for its strong reducing capabilities [36].

4. Coconut (Cocos nucifera): Coconut water or milk, containing natural sugars and vitamins, serves as a mild yet effective bioreactor for AgNP synthesis [37].

5. Terminalia chebula: Extract from the fruit of Terminalia chebula, known for its potent antioxidant and phenolic content, is effective in nanoparticle formation [38].

6. Tinospora (Tinospora cordifolia): Extracts from Tinospora cordifolia stems or leaves, rich in alkaloids, glycosides, and terpenoids, are utilized for reducing silver ions and stabilizing nanoparticles [39].

7. Black Pepper (Piper nigrum): The seed extract of black pepper, containing piperine and phenolic compounds, aids in nanoparticle synthesis and stability [40].

8. Periwinkle (Catharanthus roseus): Extracts from the leaves or flowers of Catharanthus roseus, containing alkaloids, flavonoids, and phenolics, are employed in AgNP preparation [41].

9. Eucalyptus (Eucalyptus camaldulensis): The aqueous extract from eucalyptus leaves, enriched with essential oils, tannins, and phenolic acids, is a reliable reducing agent for silver ions [42].

10. Chrysanthemum: Extract from chrysanthemum flowers, containing terpenoids, flavonoids, and phenolic acids, reduces gold ions and stabilizes AgNPs [43].

Each of these plant extracts brings its unique phytochemical profile, making them environmentally friendly and effective bioreductants in the green synthesis of silver nanoparticles.

Plant Extracts Used for Gold Nanoparticles (AuNPs) Preparation

These green methods provide better control over size, shape, and chemical composition, and avoid toxic reagents commonly used in chemical synthesis. Plant-based nanoparticle synthesis offers an eco-friendly alternative to traditional methods, showcasing the diverse applications of natural extracts [44]. Extracts from Aloe vera and Azadirachta indica leaf extracts have been employed to produce biocompatible coatings for gold nanoparticles synthesis [45, 46]. Mimusops elengi bark has also been utilized to synthesize gold nanoparticles (AuNPs), highlighting the versatility of plant materials [47]. Yu et al. demonstrated the potential of aqueous extracts from Citrus maxima (C. maxima) in producing gold nanoparticles [48]. In another study, Narayanan and Sakthive synthesized nanoparticles in the size range of 7–58 nm with diverse shapes, such as spherical, triangular, and decahedral, using leaf extracts of Coriandrum sativum (coriander) [49]. The morphology of nanoparticles can be influenced by the extract concentration, as shown by Kasthuri et al. Using a dilute Phyllanthus amarus extract, they synthesized triangular and hexagonal nanoparticles, while increasing the concentration favored the formation of spherical particles [50]. Noruzi et al. demonstrated the rapid formation of AuNPs utilizing Rosa hybrida petal extracts, completing the entire reaction within five minutes at room temperature, showcasing the efficiency of this method. The successful formation of nanoparticles was confirmed through various analytical techniques [89]. Daisy and Saipriya utilized aqueous extracts of Cassia fistula to produce nanoparticles between 55 and 98 nm, showcasing not only their synthesis capabilities but also their hypoglycemic properties [51]. Edison and Sethuraman synthesized nanoparticles measuring 6–60 nm using extracts from Terminalia chebula [52]. Liu et al. explored the use of chrysanthemum and tea beverages to produce gold nanoparticles and demonstrated their application in evaluating antioxidant properties [70]. Dubey et al. demonstrated that carbonyl groups in Rosa rugosa extracts facilitated the reduction of metal ions, as confirmed by FTIR analysis. The zeta potential of the synthesized nanoparticles varied with pH, with the size increasing from 50 to 250 nm under strongly acidic conditions [80]. Similarly, Benincasa hispida seed extract was used in AuNP synthesis, where carboxylic groups (COOH) in the extract were converted to COO^- during the reduction process. These carboxylate groups in proteins acted as surfactants, stabilizing the nanoparticles through electrostatic interactions, resulting in particle sizes ranging from 10 to 30 nm depending on synthesis parameters [53]. The green synthesis of gold nanoparticles (AuNPs) using plant-based extracts has proven to be an efficient and eco-friendly approach. Similarly, aqueous extracts of cypress were employed for AuNP synthesis, where extract concentration and pH significantly influenced the size of the resulting nanoparticles, highlighting the critical role of these parameters in nanoparticle synthesis [54]. Aromal and Philip reported the use of fenugreek (Trigonella foenum-graecum) aqueous extracts, which acted as both reducing and stabilizing agents, to produce AuNPs. By optimizing synthesis conditions, nanoparticles with sizes between 15 and 25 nm were obtained [55]. Sujitha and Kannan utilized Citrus fruit leaf extracts for the biosynthesis of AuNPs, yielding nanoparticles with diverse shapes and sizes, ranging from 15 to 80 nm, as confirmed by TEM analysis [56]. Other plant extracts have also been explored for AuNP synthesis. The bark of *Mimusops elengi* facilitated the green synthesis of gold nanoparticles under mild conditions, while Stevia leaves and *Ocimum sanctum (holy basil)* leaves provided effective aqueous extracts for nanoparticle production [57]. *Eucalyptus oleosa* leaf extracts served as reducing agents for the synthesis of stable gold nanoparticles, emphasizing the versatility of plant-based reducing agents in green chemistry [58]. Additionally, *Nepenthes khasiana* was utilized for the biosynthesis of gold nanoparticles, producing triangular and spherical particles with sizes ranging between 50 and 80 nm. Extracts from Sphaeranthus indicus also proved effective in synthesizing gold nanoparticles, further broadening the scope of plant-mediated nanotechnology [59].

Different plant parts that contain various biological compounds facilitating the reduction and capping of gold ions to stable gold nanoparticles are outlined below:

1. **Golden Shower Tree (*Cassia fistula*):** The flower or fruit extract, rich in flavonoids, phenolic compounds, and alkaloids, serves as an efficient reducing agent for gold ions [60].
2. **Tea (Camellia sinensis):** Tea extracts, especially green tea, are abundant in catechins, polyphenols, and antioxidants, making them highly effective for reducing and stabilizing gold ions [61].
3. **Natural Rubber (*Hevea brasiliensis*):** Latex or extract from natural rubber, containing proteins and polyisoprenes, aids in the bioreduction and stabilization of gold nanoparticles [62].
4. **Aloe Vera (*Aloe vera*):** Aloe vera gel or leaf extract, containing polysaccharides, vitamins, and amino acids, provides a gentle yet effective reduction environment for AuNP formation [63].
5. **Lemongrass (*Cymbopogon citratus*):** Lemongrass extract, abundant in essential oils, flavonoids, and phenolic acids, acts as a rapid and efficient reducing agent for gold ions [64].
6. **Mimusops elengi:** The extract from the bark or seeds, enriched with flavonoids and tannins, is utilized for gold nanoparticle synthesis due to its reducing potential [65].
7. **Japanese Honeysuckle (*Lonicera japonica*):** The flower extract, rich in polyphenols and flavonoids, facilitates the synthesis and stabilization of AuNPs [66].
8. **Pleuropterus multiflorus (Roots):** Root extract of *Pleuropterus multiflorus*, known for its phytochemical richness, is effective in reducing and stabilizing gold ions [67].
9. **Oleander (*Nerium oleander*):** Extract from the leaves or flowers of *Nerium oleander*, containing alkaloids and phenolic compounds, is employed in AuNP preparation [68].

These plant extracts offer eco-friendly and sustainable routes for gold nanoparticle synthesis, leveraging their unique biomolecules for effective reduction and stabilization.

Plant Extracts Used for Platinum Nanoparticles (PtNPs) Preparation

Platinum nanoparticles (PtNPs) can be synthesized using green methods, with plant extracts gaining significant attention due to their eco-friendly and sustainable nature [69]. Various plant parts, such as leaves, seeds, and whole plants, are used for the synthesis. For example, *Ocimum sanctum* and *Bacopa monnieri* extracts yield particles ranging from 5 to 20 nm [70] [70, 71]. Other plants like *Anacardium occidentale* and *Crinum speciosum* stabilize PtNPs of sizes between ~4 and ~55 nm [69, 72]. Additionally, plant seeds like guar gum result in PtNPs around 6 nm in size, and materials like wood, fulvic acid, and lignin have been used to create nanoparticles in the range of

2.3 to 8 nm. Whole plant extracts, such as those from *T. laevigatum* and *P. gymnospora*, can produce nanoparticles sized from 2 to 50 nm, depending on the synthesis conditions. The synthesis process is influenced by factors such as temperature, extract concentration, and reaction time, which control the size, shape, and stability of the nanoparticles. Green synthesis methods avoid toxic chemicals, using plant extracts as both reducing and stabilizing agents, offering a safe and sustainable approach. These methods enable the production of PtNPs with controlled properties, making them ideal for various applications in catalysis, medicine, and material sciences.

Antibacterial and Antifungal Applications of Metal Nanoparticles

Mechanism for the use of nanoparticles, particularly gold (AuNPs), silver (AgNPs), and platinum nanoparticles (PtNPs), has emerged as a promising approach in combating bacterial and fungal infections. These nanoparticles exhibit unique properties, such as their small size, high surface area, and ability to generate reactive oxygen species (ROS), which contribute to their potent antimicrobial effects. Their mechanisms of action include (figure 2).

Release of M+ Ions: Silver ions released from MNPs exhibit cytotoxic effects, damaging microbial cells internally and externally.

Disruption of Cell Walls: MNPs interfere with microbial cell wall integrity, leading to structural damage and eventual cell lysis.

Generation of ROS: AMNPs catalyze ROS formation, which damages organelles, DNA, and other cellular components.

DNA damage: Reactive oxygen species (ROS) are highly reactive molecules that possess the potential to inflict damage on DNA. This damage can occur through direct interaction with the DNA itself or by compromising the proteins responsible for its maintenance. The presence of ROS can lead to various forms of DNA damage, such as the oxidation of nucleotide bases and the occurrence of strand breaks.

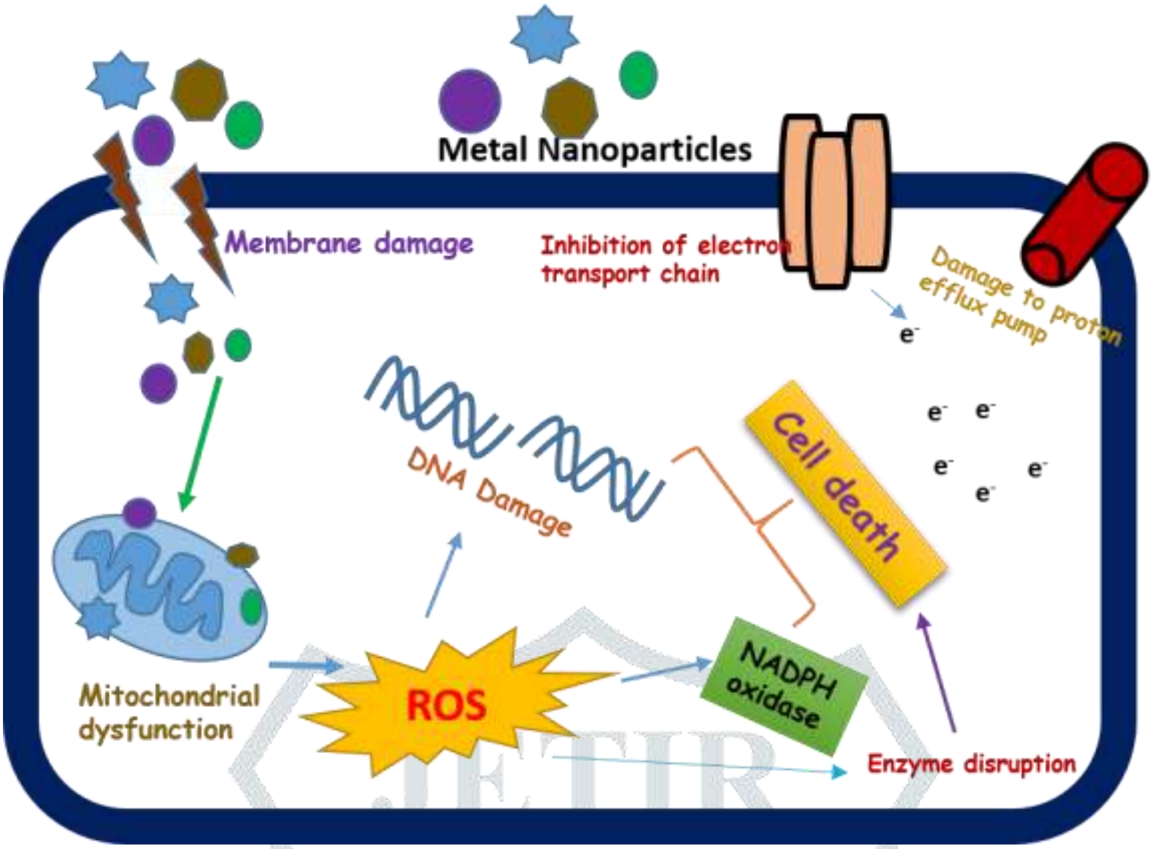

***Fig 2**: schematic cell death mechanism of bacteria/fungal by metal nanoparticles*

Silver Nanoparticles (AgNPs)

Plant-based synthesis methods have been explored to produce AgNPs with enhanced antimicrobial activity. For instance, neem (Azadirachta indica) leaf extracts were used to synthesize AgNPs, demonstrating significant bacterial inhibition [34]. Similarly, Coffee arabica seed extract was utilized to produce nanoparticles (20–30 nm) that effectively inhibited *E. coli* and *S. aureus* [73]. Other studies reported that AgNPs synthesized from Cocos nucifera extracts (22 nm) exhibited potent antimicrobial activity against *Salmonella paratyphi*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Aeromonas sp.*, *Acinetobacter sp. and Citrobacter sp.* [74, 75]

AgNPs also show promise in antifungal applications, particularly against strains like *Candida albicans*, *Saccharomyces cerevisiae* and *Trichophyton mentagrophytes* [76, 77]. Their antifungal efficacy improves when combined with heterocyclic compounds like pyrazoles or thiazolidines, enhancing ROS production and causing fungal cell wall damage [78].

Gold Nanoparticles (AuNPs)

Gold nanoparticles have a long history of use in medical applications due to their excellent biocompatibility and antimicrobial properties. AuNPs interact with sulfur- and phosphorus-containing biomolecules, disrupting critical enzymes and cellular processes such as respiration and ATP synthesis. They also enhance ROS production, damaging DNA, proteins, and cell membranes, which ultimately leads to microbial death.

Studies have demonstrated the size- and shape-dependent effects of AuNPs, with smaller nanoparticles (e.g., <10 nm) exhibiting enhanced antibacterial and antifungal activities. Pseudomonas aeruginosa, Klebsiella pneumoniae, and Salmonella choleraesuis, with mechanisms linked to ATP production and mitochondrial membrane disruption [79, 80].

In combating fungal infections, AuNPs are particularly effective against pathogens like Candida albicans and Trichophyton mentagrophytes, leveraging their nanoscale size to penetrate microbial cell walls [81, 82]. These nanoparticles disrupt fungal mycelial morphology and cellular integrity, making them a potent tool in antifungal therapies.

Platinum Nanoparticles (PtNPs)

PtNPs exhibit strong antibacterial and antifungal properties. Early studies revealed their ability to inhibit bacterial growth, with smaller particles (2–5 nm) proving particularly effective by generating reactive oxygen species (ROS) [69]. PVP-coated PtNPs (2–20 nm) show size-dependent effects, with smaller particles (<3 nm) causing significant bacterial toxicity, while larger ones mainly interact with membranes. Against fungi, PtNPs disrupt membranes, induce ROS, and cause DNA damage, showing potential as safer alternatives to conventional antifungals.

Conclusions

Plant-based synthesis of metal nanoparticles represents a significant milestone in advancing sustainable and eco-friendly nanotechnology. By utilizing plant extracts as natural reducing and stabilizing agents, this approach offers a green alternative to conventional chemical and physical methods, addressing environmental and economic concerns. Among the various nanoparticles synthesized, silver nanoparticles (AgNPs) are particularly valued for their rapid, broad-spectrum antimicrobial properties, while gold nanoparticles (AuNPs) are noted for their exceptional biocompatibility, making them ideal for prolonged biological interactions. The versatility and adaptability of this synthesis process—enabled by the selection of plant species, parts, and process parameters—highlight its potential for customization to meet diverse applications in medicine, environmental remediation, and industrial processes.

However, challenges such as variability in nanoparticle synthesis due to differences in phytochemical composition, scalability, and the need for precise understanding of biological mechanisms remain barriers to wider adoption. Furthermore, ensuring safety, optimizing production protocols, and mitigating potential environmental impacts are critical areas that require ongoing attention.

Future Scope

Standardization of Synthesis Protocols: Developing standardized methodologies to ensure consistency and reproducibility in nanoparticle synthesis across different plant sources is essential. This will enhance reliability and commercial scalability. Mechanistic Studies: More in-depth research into the precise mechanisms of nanoparticle formation and their interactions with biological systems and pathogens is necessary to improve efficacy and safety. Toxicity and Environmental Impact Assessment: Comprehensive studies on the long-term toxicity and environmental effects of plant-synthesized nanoparticles are crucial to ensure their safe use in clinical and industrial applications. Scale-up and Industrial Applications: Research into cost-effective and scalable production techniques will enable the large-scale application of plant-based nanoparticles in industries such as healthcare, agriculture, and energy. Exploration of Diverse Plant Sources: Investigating a wider range of plant species and their parts for nanoparticle synthesis may reveal unique phytochemicals that offer enhanced or novel functionalities. Integration with Advanced Technologies: Combining plant-based synthesis with advanced technologies like 3D printing, microfluidics, and artificial intelligence could open new pathways for creating complex nanostructures and tailored applications. Multifunctional Nanoparticles: Focus on the development of multifunctional nanoparticles capable of simultaneous diagnostic, therapeutic, and imaging roles, particularly for use in precision medicine and biosensing. Environmental Applications: Expanding research into the application of nanoparticles for environmental remediation, including water purification, pollutant degradation, and energy storage, aligns with global sustainability goals.

References

1. Christian, P., et al., *Nanoparticles: structure, properties, preparation and behaviour in environmental media.* Ecotoxicology, 2008. **17**(5): p. 326-343.
2. Mody, V.V., et al., *Introduction to metallic nanoparticles.* Journal of Pharmacy and Bioallied Sciences, 2010. **2**(4).
3. Tweney, R., *Faraday's Discovery of Induction: A Cognitive Approach*. 1985. p. 189-209.
4. Sreeprasad, T.S. and T. Pradeep, *Noble Metal Nanoparticles*, in *Springer Handbook of Nanomaterials*, R. Vajtai, Editor. 2013, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 303-388.
5. Daraee, H., et al., *Application of gold nanoparticles in biomedical and drug delivery.* Artificial Cells, Nanomedicine, and Biotechnology, 2016. **44**(1): p. 410-422.
6. Siddiqi, K.S. and A. Husen, *Green Synthesis, Characterization and Uses of Palladium/Platinum Nanoparticles.* Nanoscale Research Letters, 2016. **11**(1): p. 482.
7. Pareek, V.B., Arpit; Gupta, Rinki; Jain, Navin; Panwar, Jitendra, *Synthesis and Applications of Noble Metal Nanoparticles: A Review.* Advanced Science, Engineering and Medicine, 2016. **9**(18): p. 527-544.
8. Patil, M.P. and G.-D. Kim, *Eco-friendly approach for nanoparticles synthesis and mechanism behind antibacterial activity of silver and anticancer activity of gold nanoparticles.* Applied Microbiology and Biotechnology, 2016. **101**(1): p. 79-92.
9. Vijayaraghavan, K. and T. Ashokkumar, *Plant-mediated biosynthesis of metallic nanoparticles: A review of literature, factors affecting synthesis, characterization techniques and applications.* Journal of Environmental Chemical Engineering, 2016. **5**(5): p. 4866-4883.
10. Zheng, B., et al., *Plant-mediated synthesis of platinum nanoparticles and its bioreductive mechanism.* Journal of Colloid and Interface Science, 2013. **396**: p. 138-145.
11. Siddiqi, K.S. and A. Husen, *Recent advances in plant-mediated engineered gold nanoparticles and their application in biological system.* Journal of Trace Elements in Medicine and Biology, 2016. **40**: p. 10-23.
12. Ahmed, S., et al., *A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise.* Journal of Advanced Research, 2016. **7**(1): p. 17-28.
13. Dolez, P.I., *Chapter 1.1 - Nanomaterials Definitions, Classifications, and Applications*, in *Nanoengineering*, P.I. Dolez, Editor. 2015, Elsevier: Amsterdam. p. 3-40.
14. Bhatia, S., *Nanoparticles Types, Classification, Characterization, Fabrication Methods and Drug Delivery Applications*, in *Natural Polymer Drug Delivery Systems: Nanoparticles, Plants, and Algae*, S. Bhatia, Editor. 2016, Springer International Publishing: Cham. p. 33-93.
15. Parveen, K., V. Banse, and L. Ledwani, *Green synthesis of nanoparticles: Their advantages and disadvantages.* AIP Conference Proceedings, 2016. **1724**(1): p. 020048.
16. Siegel, J., et al., *Green Synthesized Noble Metals for Biological Applications.* Materials Today: Proceedings, 2016. **3**(2): p. 608-616.

17. Gardea-Torresdey, J.L., et al., *Alfalfa Sprouts: A Natural Source for the Synthesis of Silver Nanoparticles.* Langmuir, 2003. **19**(4): p. 1357-1361.
18. Mittal, A.K., Y. Chisti, and U.C. Banerjee, *Synthesis of metallic nanoparticles using plant extracts.* Biotechnology Advances, 2013. **31**(2): p. 346-356.
19. Ghaffari-Moghaddam, M., et al., *Green synthesis of silver nanoparticles using plant extracts.* Korean Journal of Chemical Engineering, 2014. **31**(4): p. 548-557.
20. Veisi, H., et al., *Green and effective route for the synthesis of monodispersed palladium nanoparticles using herbal tea extract (Stachys lavandulifolia) as reductant, stabilizer and capping agent, and their application as homogeneous and reusable catalyst in Suzuki coupling reactions in water.* Applied Organometallic Chemistry, 2015. **29**(1): p. 26-32.
21. Apriandanu, D.O.B. and Y. Yulizar, *The role of aqueous leaf extract of Tinospora crispa as reducing and capping agents for synthesis of gold nanoparticles.* IOP Conference Series: Materials Science and Engineering, 2017. **188**(1): p. 012013.
22. Shameli, K., et al. *Green Biosynthesis of Silver Nanoparticles Using Callicarpa maingayi Stem Bark Extraction*. Molecules, 2012. **17**, 8506-8517 DOI: 10.3390/molecules17078506.
23. Jeyaraj, M., et al., *An investigation on the cytotoxicity and caspase-mediated apoptotic effect of biologically synthesized silver nanoparticles using Podophyllum hexandrum on human cervical carcinoma cells.* Colloids Surf B Biointerfaces, 2013. **102**: p. 708-17.
24. Krishnaraj, C., et al., *Synthesis of silver nanoparticles using Acalypha indica leaf extracts and its antibacterial activity against water borne pathogens.* Colloids and Surfaces B: Biointerfaces, 2010. **76**(1): p. 50-56.
25. Veeraputhiran, V., *Bio-catalytic synthesis of silver nanoparticles.* Int J Chem Tech Res, 2013. **5**(5): p. 2555-2562.
26. Sun, Q., et al., *Green synthesis of silver nanoparticles using tea leaf extract and evaluation of their stability and antibacterial activity.* Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2014. **444**: p. 226-231.
27. Gopinath, V., et al., *Biosynthesis of silver nanoparticles from Tribulus terrestris and its antimicrobial activity: A novel biological approach.* Colloids and Surfaces B: Biointerfaces, 2012. **96**: p. 69-74.
28. Masurkar, S.A., et al., *Rapid Biosynthesis of Silver Nanoparticles Using Cymbopogan Citratus (Lemongrass) and its Antimicrobial Activity.* Nano-Micro Letters, 2011. **3**(3): p. 189-194.
29. Sadeghi, B. and F. Gholamhoseinpoor, *A study on the stability and green synthesis of silver nanoparticles using Ziziphora tenuior (Zt) extract at room temperature.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2015. **134**: p. 310-315.
30. Subapriya, M.R.M.S., *Green synthesis of silver nanoparticles.* Int J Pharm Med Biol Sci, 2012. **1**(1): p. 54-61.
31. Ahmed, S., et al., *Green synthesis of silver nanoparticles using Azadirachta indica aqueous leaf extract.* Journal of Radiation Research and Applied Sciences, 2016. **9**(1): p. 1-7.
32. Ulug, B., et al., *Role of irradiation in the green synthesis of silver nanoparticles mediated by fig (Ficus carica) leaf extract.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2015. **135**: p. 153-161.
33. Kumar, D.A., V. Palanichamy, and S.M. Roopan, *Green synthesis of silver nanoparticles using Alternanthera dentata leaf extract at room temperature and their antimicrobial activity.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2014. **127**: p. 168-171.
34. Roy, P., et al., *Green synthesis of silver nanoparticles using Azadirachta indica leaf extract and its antimicrobial study.* Applied Nanoscience, 2017. **7**(8): p. 843-850.
35. Logaranjan, K., et al., *Shape- and Size-Controlled Synthesis of Silver Nanoparticles Using Aloe vera Plant Extract and Their Antimicrobial Activity.* Nanoscale Research Letters, 2016. **11**(1): p. 520.
36. Jha, P.K., et al., *Potential targetability of multi-walled carbon nanotube loaded with silver nanoparticles photosynthesized from Ocimum tenuiflorum (tulsi extract) in fertility diagnosis.* Journal of Drug Targeting, 2017. **25**(7): p. 616-625.
37. Elumalai, E.K., K. Kayalvizhi, and S. Silvan, *Coconut water assisted green synthesis of silver nanoparticles.* J Pharm Bioallied Sci, 2014. **6**(4): p. 241-5.
38. Espenti, C.S., K.S.V.K. Rao, and K.M. Rao, *Bio-synthesis and characterization of silver nanoparticles using Terminalia chebula leaf extract and evaluation of its antimicrobial potential.* Materials Letters, 2016. **174**: p. 129-133.
39. Selvam, K., et al., *Eco-friendly biosynthesis and characterization of silver nanoparticles using Tinospora cordifolia (Thunb.) Miers and evaluate its antibacterial, antioxidant potential.* Journal of Radiation Research and Applied Sciences, 2017. **10**(1): p. 6-12.
40. Javad, S., et al., *Evaluation of efficiency of different plants to develop silver nanoparticles.* Pak. J. Bot, 2017. **47**: p. 283-287.
41. Al-Shmgani, H.S.A., et al., *Biosynthesis of silver nanoparticles from Catharanthus roseus leaf extract and assessing their antioxidant, antimicrobial, and wound-healing activities.* Artificial Cells, Nanomedicine, and Biotechnology, 2017. **45**(6): p. 1234-1240.
42. Mohammed, A.E., *Green synthesis, antimicrobial and cytotoxic effects of silver nanoparticles mediated by Eucalyptus camaldulensis leaf extract.* Asian Pacific Journal of Tropical Biomedicine, 2015. **5**(5): p. 382-386.

43. Arokiyaraj, S., et al., *Rapid green synthesis of silver nanoparticles from Chrysanthemum indicum L and its antibacterial and cytotoxic effects: an in vitro study.* International Journal of Nanomedicine, 2014. **9**(null): p. 379-388.
44. Elia, P., et al., *Green synthesis of gold nanoparticles using plant extracts as reducing agents.* International Journal of Nanomedicine, 2014. **9**(null): p. 4007-4021.
45. Muralikrishna, T., M. Pattanayak, and P.L. Nayak, *Green synthesis of gold nanoparticles using (aloe vera) aqueous extract.* World Journal of Nano Science & Technology, 2014. **3**(2): p. 45-51.
46. Mishra, D., et al., *Green synthesis of gold nanoparticles by Azadirachta indica leaf extract and coating with Morinda citrifolia fruit extract: their characterization.* Int J Livest Res, 2017. **1**.
47. Majumdar, R., B.G. Bag, and P. Ghosh, *Mimusops elengi bark extract mediated green synthesis of gold nanoparticles and study of its catalytic activity.* Applied Nanoscience, 2016. **6**(4): p. 521-528.
48. Nakkala, J.R., R. Mata, and S.R. Sadras, *The antioxidant and catalytic activities of green synthesized gold nanoparticles from Piper longum fruit extract.* Process Safety and Environmental Protection, 2016. **100**: p. 288-294.
49. Narayanan, K.B. and N. Sakthivel, *Coriander leaf mediated biosynthesis of gold nanoparticles.* Materials Letters, 2008. **62**(30): p. 4588-4590.
50. Kasthuri, J., K. Kathiravan, and N. Rajendiran, *Phyllanthin-assisted biosynthesis of silver and gold nanoparticles: a novel biological approach.* Journal of Nanoparticle Research, 2009. **11**(5): p. 1075-1085.
51. Daisy, P. and K. Saipriya, *Biochemical analysis of Cassia fistula aqueous extract and phytochemically synthesized gold nanoparticles as hypoglycemic treatment for diabetes mellitus.* Int J Nanomedicine, 2012. **7**: p. 1189-202.
52. Edison, T.J.I. and M.G. Sethuraman, *Instant green synthesis of silver nanoparticles using Terminalia chebula fruit extract and evaluation of their catalytic activity on reduction of methylene blue.* Process Biochemistry, 2012. **47**(9): p. 1351-1357.
53. Aromal, S.A. and D. Philip, *Benincasa hispida seed mediated green synthesis of gold nanoparticles and its optical nonlinearity.* Physica E: Low-dimensional Systems and Nanostructures, 2012. **44**(7): p. 1329-1334.
54. Noruzi, M., D. Zare, and D. Davoodi, *A rapid biosynthesis route for the preparation of gold nanoparticles by aqueous extract of cypress leaves at room temperature.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2012. **94**: p. 84-88.
55. Aswathy Aromal, S. and D. Philip, *Green synthesis of gold nanoparticles using Trigonella foenum-graecum and its size-dependent catalytic activity.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2012. **97**: p. 1-5.
56. Sujitha, M.V. and S. Kannan, *Green synthesis of gold nanoparticles using Citrus fruits (Citrus limon, Citrus reticulata and Citrus sinensis) aqueous extract and its characterization.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2013. **102**: p. 15-23.
57. Lee, S.Y., et al., *Biosynthesis of Gold Nanoparticles Using Ocimum sanctum Extracts by Solvents with Different Polarity.* ACS Sustainable Chemistry & Engineering, 2016. **4**(5): p. 2651-2659.
58. Pourmortazavi, S.M., et al., *Reducing power of Eucalyptus oleosa leaf extracts and green synthesis of gold nanoparticles using the extract.* International Journal of Food Properties, 2017. **20**(5): p. 1097-1103.
59. Bhau, B.S., et al., *Green synthesis of gold nanoparticles from the leaf extract of Nepenthes khasiana and antimicrobial assay.* Advanced Materials Letters, 2015. **6**: p. 55-58.
60. Daisy, P. and K. Saipriya, *Biochemical analysis of Cassia fistula aqueous extract and phytochemically synthesized gold nanoparticles as hypoglycemic treatment for diabetes mellitus.* International journal of nanomedicine, 2012: p. 1189-1202.
61. Jia, J.-L., et al., *Biosynthesis of silver and gold nanoparticles using Huangdan (Camellia sinensis) leaf extract.* Synthesis and Reactivity in Inorganic, Metal-Organic, and Nano-Metal Chemistry, 2015. **45**(7): p. 941-946.
62. Tao, J., et al., *In situ synthesis of natural rubber latex-supported gold nanoparticles for flexible SERS substrates.* Rsc Advances, 2015. **5**(61): p. 49168-49174.
63. Parthasarathy, G., et al., *Synthesis of Nano Particles From Aloe Vera Extract–Review Paper.* Imperial Journal of Interdisciplinary Research, 2016. **2**(10): p. 1570-75.
64. Murugan, K., et al., *Cymbopogon citratus-synthesized gold nanoparticles boost the predation efficiency of copepod Mesocyclops aspericornis against malaria and dengue mosquitoes.* Experimental Parasitology, 2015. **153**: p. 129-138.
65. Majumdar, R., B.G. Bag, and P. Ghosh, *Mimusops elengi bark extract mediated green synthesis of gold nanoparticles and study of its catalytic activity.* Applied Nanoscience, 2016. **6**: p. 521-528.
66. Nagajyothi, P.C., et al., *Green synthesis of silver and gold nanoparticles using Lonicera Japonica flower extract.* Bulletin of the Korean Chemical Society, 2012. **33**(8): p. 2609-2612.
67. Castro-Aceituno, V., et al., *Pleuropterus multiflorus (Hasuo) mediated straightforward eco-friendly synthesis of silver, gold nanoparticles and evaluation of their anti-cancer activity on A549 lung cancer cell line.* Biomedicine & Pharmacotherapy, 2017. **93**: p. 995-1003.
68. Tahir, K., et al., *Nerium oleander leaves extract mediated synthesis of gold nanoparticles and its antioxidant activity.* Materials Letters, 2015. **156**: p. 198-201.
69. Tahir, K., et al., *Facile and green synthesis of phytochemicals capped platinum nanoparticles and in vitro their superior antibacterial activity.* Journal of Photochemistry and Photobiology B: Biology, 2017. **166**: p. 246-251.

70. Prabhu, N. and T. Gajendran, *Green synthesis of noble metal of platinum nanoparticles from Ocimum sanctum (Tulsi) Plant-extracts.* IOSR J. Biotechnol. Biochem, 2017. **3**(1): p. 107-112.
71. Nellore, J., C. Pauline, and K. Amarnath, *Bacopa monnieri phytochemicals mediated synthesis of platinum nanoparticles and its neurorescue effect on 1-methyl 4-phenyl 1, 2, 3, 6 tetrahydropyridine-induced experimental parkinsonism in zebrafish.* Journal of neurodegenerative diseases, 2013. **2013**(1): p. 972391.
72. Sheny, D.S., D. Philip, and J. Mathew, *Synthesis of platinum nanoparticles using dried Anacardium occidentale leaf and its catalytic and thermal applications.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2013. **114**: p. 267-271.
73. Dhand, V., et al., *Green synthesis of silver nanoparticles using Coffea arabica seed extract and its antibacterial activity.* Materials Science and Engineering: C, 2016. **58**: p. 36-43.
74. Govarthanan, M., et al., *Low-cost and eco-friendly synthesis of silver nanoparticles using coconut (Cocos nucifera) oil cake extract and its antibacterial activity.* Artificial Cells, Nanomedicine, and Biotechnology, 2016. **44**(8): p. 1878-1882.
75. Singh, J., et al., *A review on green synthesis and characterization of silver nanoparticles and their applications: a green nanoworld.* World J. Pharm. Pharm. Sci, 2016. **6**(7).
76. Nasrollahi, A., K. Pourshamsian, and P. Mansourkiaee, *Antifungal activity of silver nanoparticles on some of fungi.* International Journal of Nano Dimension, 2010. **1**.
77. Atef, A.H., K.M. Mogda, and M. Hh, *Biosynthesis of silver nanoparticles (AgNps)(a model of metals) by Candida albicans and its antifungal activity on Some fungal pathogens (Trichophyton mentagrophytes and Candida albicans).* NY Sci. J, 2013. **6**: p. 27-43.
78. Hwang, I.s., et al., *Silver nanoparticles induce apoptotic cell death in Candida albicans through the increase of hydroxyl radicals.* The FEBS journal, 2012. **279**(7): p. 1327-1338.
79. Malarkodi, C., et al., *Eco-friendly synthesis and characterization of gold nanoparticles using Klebsiella pneumoniae.* Journal of Nanostructure in Chemistry, 2013. **3**: p. 1-7.
80. Afonso, A.S., et al., *Electrochemical detection of Salmonella using gold nanoparticles.* Biosensors and Bioelectronics, 2013. **40**(1): p. 121-126.
81. Sherwani, M.A., et al., *Gold nanoparticle-photosensitizer conjugate based photodynamic inactivation of biofilm producing cells: potential for treatment of C. albicans infection in BALB/c mice.* PLoS One, 2015. **10**(7): p. e0131684.
82. Maliszewska, I., et al., *Enhancement of the efficacy of photodynamic inactivation of Candida albicans with the use of biogenic gold nanoparticles.* Photochemistry and Photobiology, 2017. **93**(4): p. 1081-1090.