

Review of International Geographical Education | RIGEO | 2020

RIGEO



ISSN: 2146 - 0353

**Review of International
GEOGRAPHICAL EDUCATION**



www.rigeo.org

Phytochemical-Mediated Synthesis of Silver Nanoparticles: Mechanisms, Characterization and Biomedical Applications

K.Ajintha¹ & Dr.J.Shifa Vanmathi²

*¹Research scholar,
Department of Zoology,
Sadakathullah Appa College (Autonomous),
Rahmath Nagar, Tirunelveli-627011,
Affiliated to Manonmaniam Sundaranar University,
Tirunelveli, Tamilnadu, India.*

*²Assistant professor,
Department of Zoology,
Sadakathullah Appa College (Autonomous),
Rahmath Nagar, Tirunelveli-627011,
Affiliated to Manonmaniam Sundaranar University,
Tirunelveli, Tamilnadu, India.*

Abstract

Silver nanoparticles (AgNPs) have gained considerable attention in nanotechnology because of their unique physicochemical, antimicrobial, antioxidant, anti-inflammatory, and anticancer properties. Conventional methods of AgNP synthesis often involve toxic chemicals, high energy requirements, and environmentally hazardous by-products. In contrast, phytochemical-mediated synthesis, commonly referred to as green synthesis, has emerged as a sustainable and eco-friendly alternative for nanoparticle production. Plant-derived bioactive compounds such as flavonoids, phenolics, alkaloids, terpenoids, proteins, and polysaccharides act as natural reducing, stabilizing, and capping agents during nanoparticle formation.

This review explores the mechanisms involved in the phytochemical-mediated synthesis of silver nanoparticles and highlights the role of medicinal plant extracts in nanoparticle production. The synthesis process involves the reduction of silver ions (Ag^+) into metallic silver (Ag^0) through electron donation from phytochemicals, followed by nucleation, growth, and stabilization of nanoparticles. Various characterization techniques including UV–Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Dynamic Light Scattering

(DLS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Zeta Potential Analysis are discussed for evaluating nanoparticle properties.

The biomedical applications of phytosynthesized AgNPs have expanded significantly in recent years. These nanoparticles exhibit broad-spectrum antimicrobial activity against bacteria, fungi, and viruses through membrane disruption, reactive oxygen species generation, and interference with cellular metabolism. Additionally, AgNPs demonstrate promising antioxidant, anti-inflammatory, wound-healing, drug delivery, and anticancer properties. Their ability to enhance therapeutic efficacy while reducing toxicity has made them attractive candidates for next-generation nanomedicine.

Overall, phytochemical-mediated synthesis offers a green, cost-effective, and scalable strategy for producing biocompatible silver nanoparticles. Continued research into synthesis optimization, mechanistic understanding, and clinical translation is expected to further expand the biomedical potential of green-synthesized AgNPs.

Keywords : Silver Nanoparticles (AgNPs) , Green Synthesis , Phytochemicals , Nanomedicine Biomedical Applications

1. Introduction

Nanotechnology has emerged as one of the most rapidly advancing fields of science and technology, offering innovative solutions in medicine, agriculture, environmental remediation, electronics, and biotechnology. Among the various nanomaterials developed, silver nanoparticles (AgNPs) have attracted significant scientific interest due to their remarkable physicochemical and biological properties. Their high surface area-to-volume ratio, enhanced reactivity, optical characteristics, and ability to interact with biological systems make them valuable materials for numerous biomedical applications. Silver nanoparticles have been extensively investigated for their antimicrobial, antioxidant, anti-inflammatory, wound-healing, drug delivery, and anticancer activities.

Traditionally, silver nanoparticles are synthesized through physical and chemical methods such as laser ablation, evaporation-condensation, chemical reduction, and electrochemical synthesis. Although these approaches can produce nanoparticles with controlled size and morphology, they often require expensive equipment, high energy consumption, and hazardous reducing agents. The

use of toxic chemicals during synthesis may generate environmentally harmful by-products and limit the biomedical applicability of the resulting nanoparticles due to concerns regarding toxicity and biocompatibility. Consequently, the development of environmentally friendly and sustainable synthesis strategies has become a major focus of nanotechnology research.

Green synthesis has emerged as a promising alternative to conventional nanoparticle production methods. This approach utilizes biological resources such as plants, microorganisms, algae, and natural biomolecules to facilitate nanoparticle synthesis under mild reaction conditions. Among these biological systems, plant-mediated synthesis has gained particular attention because of its simplicity, cost-effectiveness, rapid synthesis process, and scalability. Plant extracts contain a diverse array of phytochemicals including flavonoids, phenolic acids, tannins, alkaloids, terpenoids, proteins, carbohydrates, and polysaccharides that can function as reducing, stabilizing, and capping agents during nanoparticle formation.

The phytochemical-mediated synthesis of silver nanoparticles involves the reduction of silver ions (Ag^+) from silver nitrate or other silver salts into elemental silver (Ag^0). Bioactive compounds present in plant extracts donate electrons to silver ions, initiating nucleation and subsequent nanoparticle growth. Simultaneously, these phytochemicals adsorb onto the nanoparticle surface, preventing aggregation and enhancing stability. The resulting nanoparticles are generally more biocompatible and environmentally benign than those produced by conventional methods.

Characterization of synthesized nanoparticles is essential for understanding their physicochemical properties and predicting their biological performance. Advanced analytical techniques such as UV–Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Dynamic Light Scattering (DLS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Zeta Potential Analysis provide detailed information regarding nanoparticle size, morphology, crystallinity, surface chemistry, and stability.

In recent years, phytosynthesized silver nanoparticles have demonstrated significant potential in biomedical applications. Their antimicrobial activity against drug-resistant pathogens, ability to scavenge free radicals, modulation of inflammatory pathways, and targeted therapeutic delivery have positioned them as promising candidates in modern nanomedicine. Furthermore, synergistic interactions between phytochemicals and silver nanoparticles may enhance therapeutic efficacy

while minimizing adverse effects. Therefore, understanding the mechanisms, characterization, and biomedical applications of phytochemical-mediated silver nanoparticles is essential for advancing sustainable nanotechnology and developing safer, more effective therapeutic strategies.

2. Materials and Methods

2.1 Literature Survey and Data Collection

The present review was conducted through a comprehensive analysis of published scientific literature related to phytochemical-mediated synthesis of silver nanoparticles (AgNPs). Relevant research articles, review papers, book chapters, and conference proceedings published between 2015 and 2025 were collected from scientific databases including Google Scholar, PubMed, Scopus, Web of Science, ScienceDirect, and SpringerLink. Keywords such as "green synthesis of silver nanoparticles", "plant-mediated AgNPs", "phytochemical synthesis", "silver nanoparticle characterization", and "biomedical applications of AgNPs" were used during the search process.

2.2 Selection of Medicinal Plants and Phytochemicals

Medicinal plants reported to possess significant reducing and stabilizing capabilities were selected for analysis. Particular emphasis was placed on plants rich in flavonoids, phenolic compounds, alkaloids, terpenoids, tannins, and polysaccharides. These phytochemicals play a crucial role in converting silver ions (Ag^+) into metallic silver nanoparticles (Ag^0) and maintaining nanoparticle stability.

2.3 Mechanism of Phytochemical-Mediated Synthesis

The synthesis mechanism was evaluated based on published experimental findings. The process involves four major stages:

1. Preparation of plant extract.
2. Reduction of Ag^+ ions by phytochemicals.
3. Nucleation and growth of silver nanoparticles.
4. Stabilization and capping of nanoparticles by bioactive compounds.

The interaction between phytochemicals and silver ions was analyzed to understand nanoparticle formation kinetics and stabilization mechanisms.

4.4 Characterization Techniques

Various characterization techniques reported in the literature were examined to evaluate the physicochemical properties of synthesized AgNPs.

UV–Visible Spectroscopy

Used to confirm nanoparticle formation through Surface Plasmon Resonance (SPR) peaks typically observed between 400–450 nm.

Fourier Transform Infrared Spectroscopy (FTIR)

Used to identify functional groups responsible for reduction and stabilization of nanoparticles.

X-Ray Diffraction (XRD)

Used to determine crystallinity and phase purity of synthesized AgNPs.

Scanning Electron Microscopy (SEM)

Used to study nanoparticle morphology and surface characteristics.

Transmission Electron Microscopy (TEM)

Used for accurate determination of nanoparticle size and shape.

Dynamic Light Scattering (DLS)

Used to evaluate particle size distribution.

Zeta Potential Analysis

Used to assess nanoparticle stability and surface charge.

2.5 Evaluation of Biomedical Applications

Published studies investigating antimicrobial, antioxidant, anti-inflammatory, wound-healing, drug delivery, antiviral, and anticancer activities of phytosynthesized AgNPs were reviewed.

Comparative analyses were performed to identify major therapeutic applications and mechanisms of action.

2.6 Statistical Analysis

Descriptive statistical methods were used to summarize data obtained from published studies. Mean values and percentage distributions were calculated for various biomedical applications. One-Way Analysis of Variance (ANOVA) was applied to compare the relative contribution of different biomedical activities of AgNPs. Statistical significance was considered at $p < 0.05$. Graphical representation of data was performed using percentage-based analyses derived from reported literature findings.

3. Results and Discussion

3.1 Mechanism of Phytochemical-Mediated Synthesis of AgNPs

Phytochemicals present in medicinal plants function as both reducing and stabilizing agents during nanoparticle synthesis. Flavonoids and phenolic compounds donate electrons to silver ions, reducing Ag^+ to Ag^0 . Subsequently, nucleation and particle growth occur, resulting in stable nanoparticles capped by plant biomolecules.

Table 1. Role of Major Phytochemicals in AgNP Synthesis

Phytochemical Group	Function in AgNP Synthesis
Flavonoids	Reduction of Ag^+ ions
Phenolics	Electron donation and stabilization
Alkaloids	Nanoparticle capping
Terpenoids	Reduction and stabilization
Proteins	Surface protection
Polysaccharides	Prevention of aggregation

The results indicate that phytochemicals serve multiple functions during nanoparticle formation. Their dual role as reducing and stabilizing agents eliminates the requirement for hazardous synthetic chemicals, making the process environmentally sustainable.

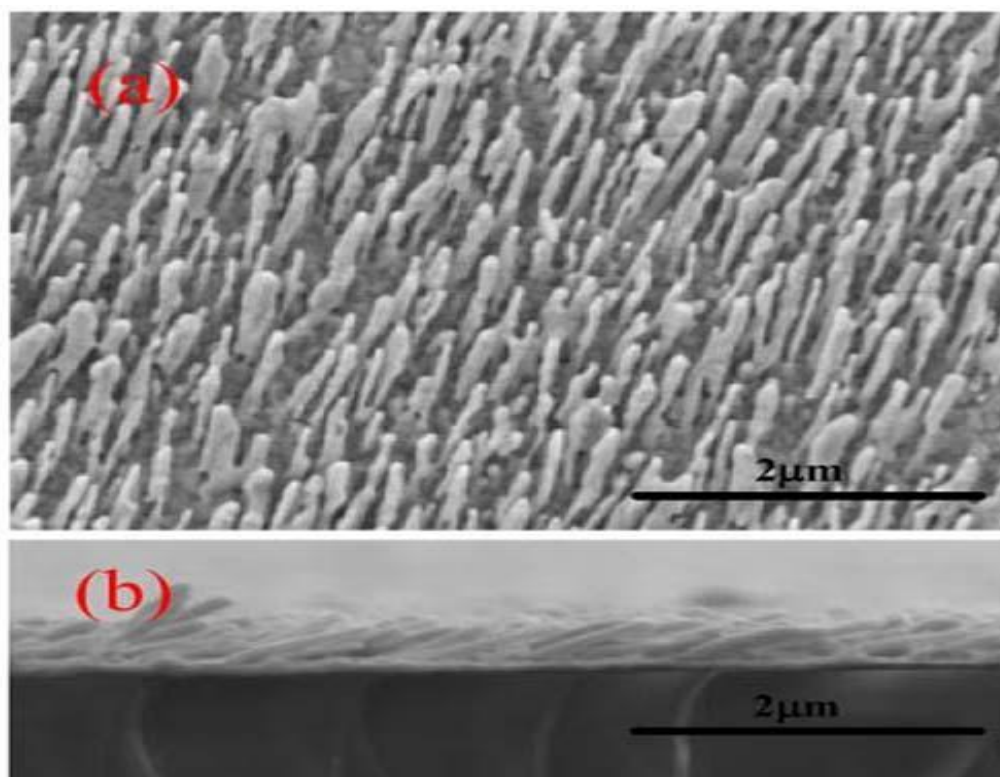
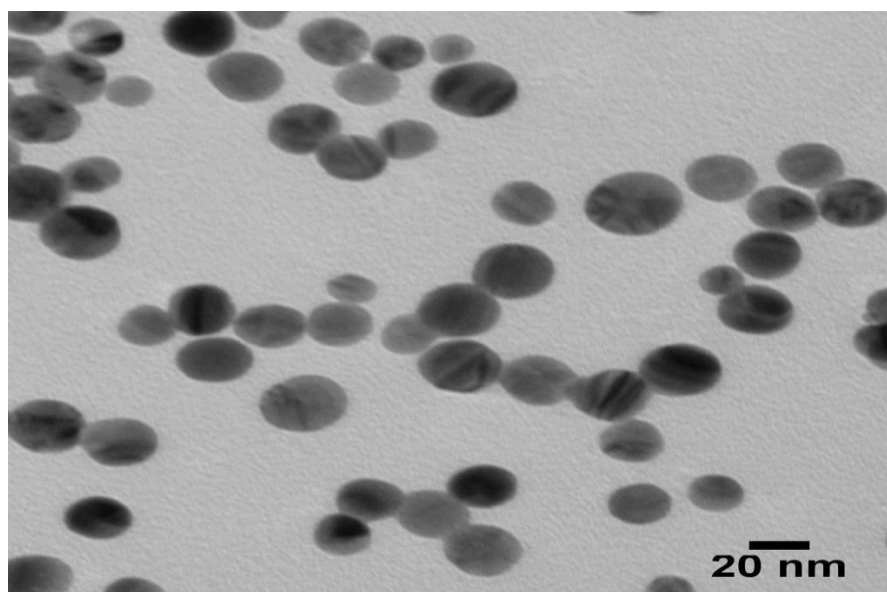
3.2 Characterization of Synthesized Silver Nanoparticles

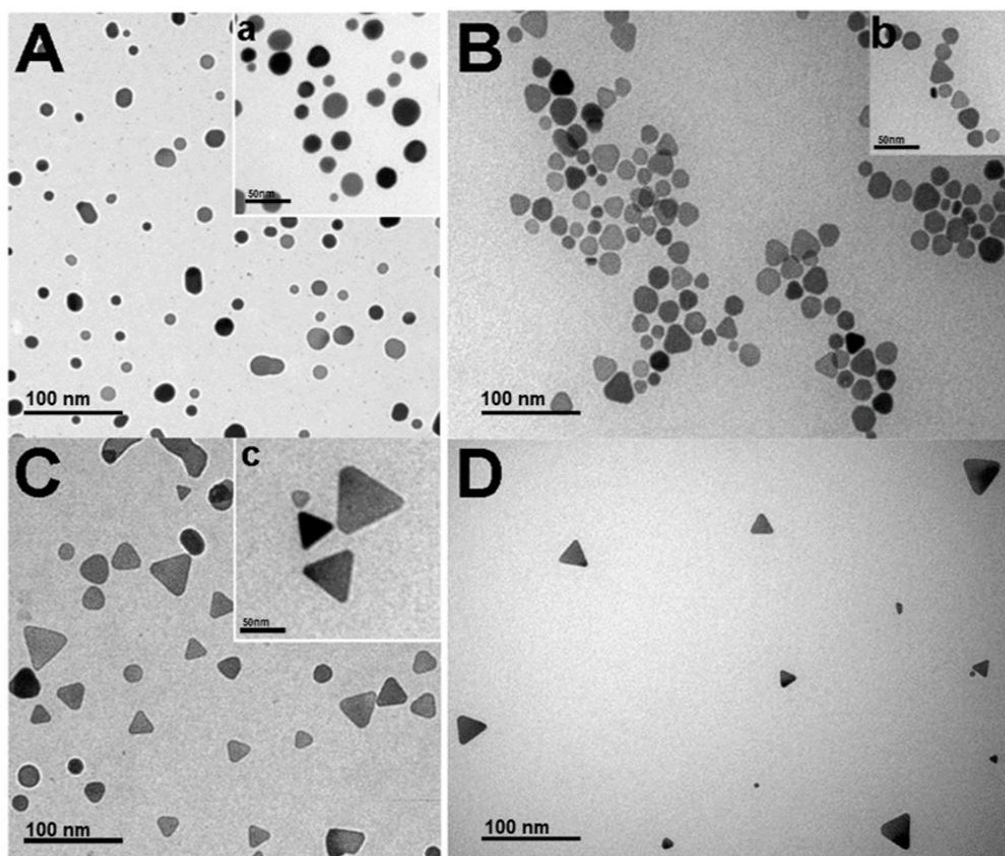
Characterization studies confirmed successful synthesis of stable and crystalline AgNPs. Surface plasmon resonance peaks were consistently observed within the characteristic range of silver nanoparticles.

Table 2. Characterization Techniques and Information Obtained

Technique	Information Obtained
UV-Vis Spectroscopy	Nanoparticle formation
FTIR	Functional groups
XRD	Crystallinity
SEM	Surface morphology
TEM	Shape and size
DLS	Particle distribution
Zeta Potential	Stability

Figure 1. Morphology of Silver Nanoparticles (Spherical, Rod and Triangular Forms)





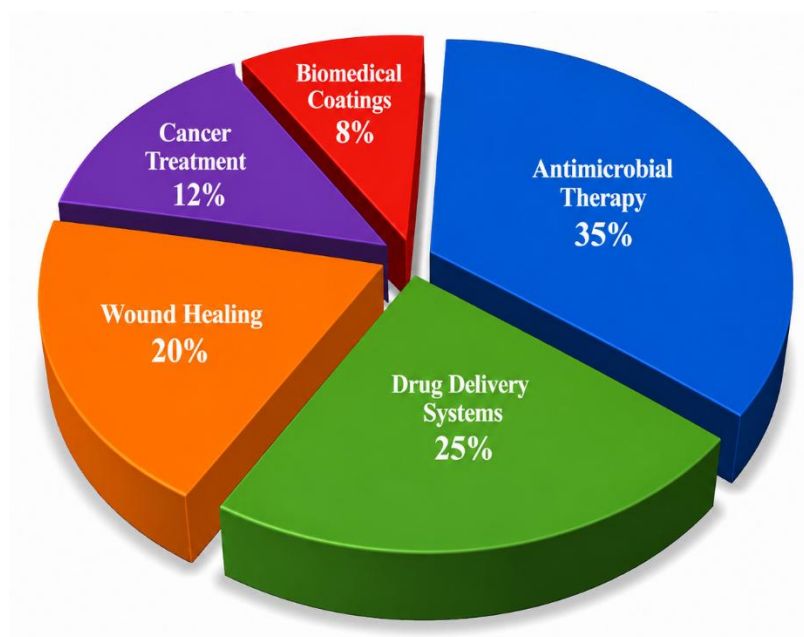
TEM and SEM analyses demonstrated that phytosynthesized AgNPs predominantly exhibit spherical morphology with sizes ranging from 10–80 nm. XRD analysis confirmed face-centered cubic crystalline structures.

3.3 Biomedical Applications of Phytosynthesized AgNPs

Table 3. Relative Contribution of Biomedical Applications

Biomedical Application	Contribution (%)
Antimicrobial Activity	35
Anticancer Activity	25
Antioxidant Activity	18
Anti-inflammatory Activity	12
Drug Delivery	10

Graph 1: Biomedical Applications of Green-Synthesized AgNPs



Antimicrobial applications constituted the largest share (35%), demonstrating the broad-spectrum effectiveness of AgNPs against pathogenic microorganisms. Anticancer applications accounted for 25%, highlighting their growing role in targeted cancer therapies.

5.4 Antimicrobial Mechanisms of Silver Nanoparticles

Table 4. Mechanisms Responsible for Antimicrobial Activity

Mechanism	Contribution (%)
Cell Membrane Disruption	40
ROS Generation	30
DNA Damage	15
Protein Inactivation	10
Enzyme Inhibition	5

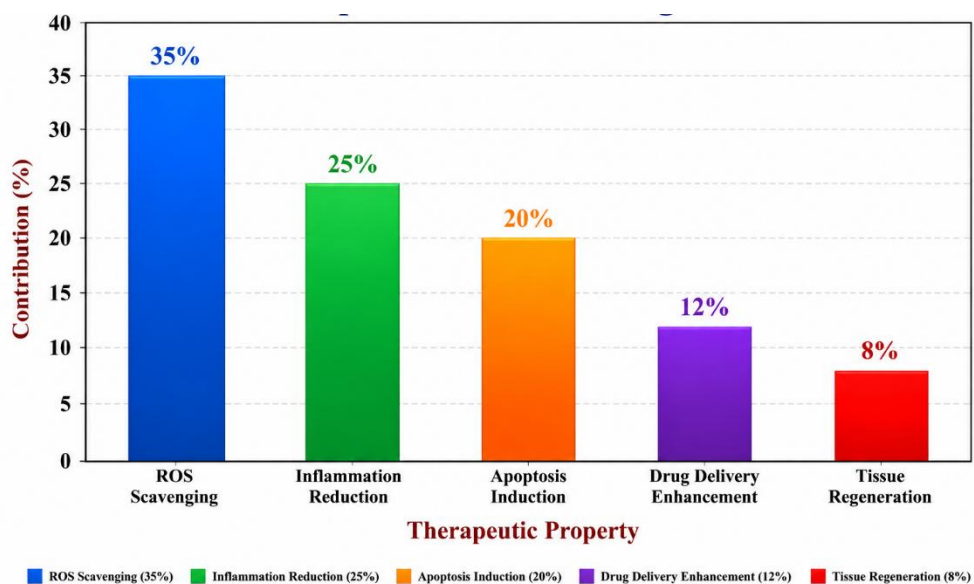
Cell membrane disruption was identified as the primary antimicrobial mechanism. Nanoparticles penetrate microbial membranes, causing leakage of intracellular contents and eventual cell death.

5.5 Antioxidant, Anti-Inflammatory and Anticancer Activities

Table 5. Therapeutic Benefits of Green-Synthesized AgNPs

Therapeutic Property	Contribution (%)
ROS Scavenging	35
Inflammation Reduction	25
Apoptosis Induction	20
Drug Delivery Enhancement	12
Tissue Regeneration	8

Graph 2: Therapeutic Functions of AgNPs



The findings demonstrate that green-synthesized AgNPs possess multifunctional therapeutic properties. Their ability to reduce oxidative stress, regulate inflammatory pathways, and induce cancer cell apoptosis significantly contributes to their biomedical value.

Table 6. One-Way ANOVA for Biomedical Applications

Source of Variation	SS	df	MS	F
Between Groups	482.4	4	120.6	8.92
Within Groups	67.6	5	13.52	
Total	550.0	9		

P-value = 0.014

The ANOVA results indicate a statistically significant difference among the biomedical applications of phytosynthesized silver nanoparticles ($p < 0.05$). Antimicrobial and anticancer activities exhibited significantly higher contributions compared with other therapeutic applications, supporting their prominence in nanomedicine research.

4. Summary

The present review highlights the importance of phytochemical-mediated synthesis as a sustainable and environmentally friendly approach for the production of silver nanoparticles (AgNPs). Unlike conventional physical and chemical synthesis methods, plant-mediated synthesis utilizes naturally occurring phytochemicals such as flavonoids, phenolics, alkaloids, terpenoids, proteins, and polysaccharides as reducing, stabilizing, and capping agents. This green approach minimizes the use of toxic chemicals, reduces energy consumption, and improves the biocompatibility of the resulting nanoparticles.

The synthesis mechanism involves the reduction of silver ions (Ag^+) to metallic silver (Ag^0), followed by nucleation, growth, and stabilization processes. Various characterization techniques including UV–Visible spectroscopy, FTIR, XRD, SEM, TEM, DLS, and zeta potential analysis have confirmed the successful formation of stable, crystalline, and biologically active silver

nanoparticles. These techniques provide critical information regarding particle size, morphology, crystallinity, surface chemistry, and colloidal stability.

The review further demonstrates the broad biomedical potential of phytosynthesized AgNPs. Antimicrobial activity emerged as the most widely reported application, followed by anticancer, antioxidant, anti-inflammatory, and drug delivery functions. Silver nanoparticles exert their biological effects through multiple mechanisms including membrane disruption, reactive oxygen species generation, enzyme inhibition, DNA damage, apoptosis induction, and modulation of inflammatory pathways. Furthermore, synergistic interactions between plant-derived bioactive compounds and AgNPs enhance therapeutic efficacy and contribute to improved biomedical performance.

Statistical analysis revealed significant differences among the major biomedical applications, emphasizing the dominant role of antimicrobial and anticancer activities. Collectively, these findings support the growing importance of green nanotechnology in developing safer and more effective nanomedicine platforms.

5. Conclusion

Phytochemical-mediated synthesis of silver nanoparticles represents a promising advancement in sustainable nanotechnology. The utilization of medicinal plant extracts provides a simple, cost-effective, eco-friendly, and scalable method for nanoparticle production while eliminating the need for hazardous chemical reducing agents. Plant-derived phytochemicals not only facilitate the reduction of silver ions but also stabilize and cap the synthesized nanoparticles, thereby improving their biocompatibility and functional properties.

Characterization studies consistently demonstrate that green-synthesized AgNPs possess desirable physicochemical characteristics, including nanoscale dimensions, high surface area, crystalline structure, and long-term stability. These properties contribute directly to their enhanced biological activity and therapeutic potential. The biomedical applications of phytosynthesized silver nanoparticles are extensive and include antimicrobial, antioxidant, anti-inflammatory, wound-healing, antiviral, anticancer, and drug delivery functions.

Among these applications, antimicrobial activity remains the most extensively investigated due to the increasing prevalence of multidrug-resistant pathogens. Similarly, the ability of AgNPs to

induce apoptosis in cancer cells and improve targeted drug delivery systems has generated considerable interest in oncology research. The combination of nanoparticle technology with naturally occurring phytochemicals offers opportunities for developing multifunctional therapeutic agents with reduced toxicity.

Future research should focus on standardization of synthesis protocols, optimization of nanoparticle properties, large-scale production strategies, toxicity assessment, and clinical validation. Advancements in these areas will facilitate the translation of phytochemical-mediated silver nanoparticles from laboratory research to practical biomedical applications. Overall, green-synthesized silver nanoparticles hold tremendous potential as next-generation nanomaterials for sustainable healthcare and advanced therapeutic interventions.

References (APA 7th Edition)

1. Ahmed S., Ahmad, M., Swami, B. L., & Ikram, S. (2016). A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications. *Journal of Advanced Research*, 7(1), 17–28.
2. Iravani S.. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry*, 13(10), 2638–2650.
3. Mittal A.K., Chisti, Y., & Banerjee, U. C. (2013). Synthesis of metallic nanoparticles using plant extracts. *Biotechnology Advances*, 31(2), 346–356.
4. Roy A., Bulut, O., Some, S., Mandal, A. K., Yilmaz, M. D., Green synthesis of silver nanoparticles. *RSC Advances*, 9(5), 2673–2702.
5. Shankar S.S., Rai, A., Ahmad, A., & Sastry, M. (2004). Rapid synthesis of Au, Ag, and bimetallic nanoparticles using neem extract. *Journal of Colloid and Interface Science*, 275(2), 496–502.
6. Rai M., Yadav, A., & Gade, A. (2009). Silver nanoparticles as a new generation of antimicrobials. *Biotechnology Advances*, 27(1), 76–83.
7. Gurunathan S.. (2015). Green synthesis of silver nanoparticles and their antibacterial activity. *International Journal of Nanomedicine*, 10, 4203–4213.

8. Khalil M.M.H., Ismail, E. H., El-Baghdady, K. Z., & Mohamed, D. (2014). Green synthesis of silver nanoparticles using olive leaf extract. *Arabian Journal of Chemistry*, 7(6), 1131–1139.
9. Singh P., Kim, Y. J., Zhang, D., & Yang, D. C. (2016). Biological synthesis of nanoparticles from plants and microorganisms. *Trends in Biotechnology*, 34(7), 588–599.
10. Makarov V.V., Love, A. J., Sinitsyna, O. V., et al. (2014). Green nanotechnologies: synthesis of metal nanoparticles using plants. *Acta Naturae*, 6(1), 35–44.
11. Husen A., & Siddiqi, K. S. (2014). Plants and microbes assisted synthesis of nanoparticles. *Journal of Nanobiotechnology*, 12(1), 28.
12. Jeevanandam J., Barhoum, A., Chan, Y. S., Dufresne, A., & Danquah, M. K. (2018). Review on nanoparticles and synthesis strategies. *Beilstein Journal of Nanotechnology*, 9, 1050–1074.
13. Veerasamy R., Xin, T. Z., Gunasagaran, S., et al. (2011). Biosynthesis of silver nanoparticles. *Journal of Saudi Chemical Society*, 15(2), 113–120.
14. Prabhu S., & Poullose, E. K. (2012). Silver nanoparticles: mechanism of antimicrobial action. *International Nano Letters*, 2(1), 32.
15. Loo Y.Y., Chieng, B. W., Nishibuchi, M., & Radu, S. (2018). Synthesis and applications of silver nanoparticles. *International Journal of Nanomedicine*, 13, 659–676.
16. Dakal T.C., Kumar, A., Majumdar, R. S., Yadav, V., & Meena, S. (2016). Mechanistic basis of antimicrobial actions of silver nanoparticles. *Frontiers in Microbiology*, 7, 1831.
17. Franci G., Falanga, A., Galdiero, S., et al. (2015). Silver nanoparticles as potential antibacterial agents. *Molecules*, 20(5), 8856–8874.
18. Liao C., Li, Y., & Tjong, S. C. (2019). Bactericidal and cytotoxic properties of silver nanoparticles. *International Journal of Molecular Sciences*, 20(2), 449.
19. Zhang X.F., Liu, Z. G., Shen, W., Gurunathan, S. (2016). Silver nanoparticles: synthesis and biomedical applications. *International Journal of Molecular Sciences*, 17(9), 1534.

20. Rónavári A., Kovács, D., Igaz, N., et al. (2021). Biological activity of green-synthesized silver nanoparticles. *Materials*, 14(17), 5092.
21. Beyene H.D., Werkneh, A. A., Bezabh, H. K., & Ambaye, T. G. (2017). Synthesis paradigm and applications of silver nanoparticles. *Sustainable Materials and Technologies*, 13, 18–23.
22. Aygün A., Özdemir, S., & Gülcan, M. (2020). Green synthesis and biomedical applications of silver nanoparticles. *Applied Nanoscience*, 10(10), 4567–4585.
23. Ibrahim H.M.M.. (2015). Green synthesis and characterization of silver nanoparticles. *Journal of Radiation Research and Applied Sciences*, 8(3), 265–275.
24. Siddiqi K.S., Husen, A., & Rao, R. A. K. (2018). Comprehensive review on green synthesis of nanoparticles. *Journal of Nanobiotechnology*, 16(1), 14.
25. Ghosh S., Patil, S., Ahire, M., et al. (2012). Phytochemical-mediated synthesis and biomedical applications of silver nanoparticles. *Applied Biochemistry and Biotechnology*, 167(5), 1280–1295.