

Review of International Geographical Education | RIGEO | 2020

RIGEO



ISSN: 2146 - 0353

**Review of International
GEOGRAPHICAL EDUCATION**



www.rigeo.org

Pharmacological Applications of Green Synthesized Silver Nanoparticles in Drug Development

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

Green synthesized silver nanoparticles (AgNPs) have emerged as promising nanomaterials in pharmaceutical research and drug development due to their unique physicochemical properties, biocompatibility, and multifunctional therapeutic activities. Conventional nanoparticle synthesis methods often involve toxic chemicals and energy-intensive procedures, whereas green synthesis utilizes biological resources such as medicinal plants, microorganisms, and natural biomolecules as reducing and stabilizing agents. This eco-friendly approach not only minimizes environmental impact but also enhances the biological functionality of nanoparticles through phytochemical surface modification. The present study reviews the pharmacological applications of green synthesized silver nanoparticles and their significance in modern drug development. Plant-derived AgNPs possess remarkable antimicrobial, antioxidant, anti-inflammatory, anticancer, antiviral, and wound-healing properties. These biological activities are largely attributed to their nanoscale dimensions, high surface area-to-volume ratio, enhanced cellular uptake, and synergistic interactions between silver and phytochemicals. Green synthesized AgNPs have demonstrated substantial efficacy against drug-resistant pathogens, oxidative stress-related disorders, inflammatory diseases, and various cancer cell lines. Recent advances in nanomedicine have

enabled the incorporation of silver nanoparticles into targeted drug delivery systems, controlled-release formulations, tissue engineering scaffolds, biosensors, and biomedical coatings. Their ability to improve drug bioavailability, stability, and therapeutic efficiency has made them attractive candidates for next-generation pharmaceutical formulations. Furthermore, silver nanoparticles facilitate enhanced permeability and retention (EPR)-mediated tumor targeting, thereby improving anticancer drug delivery while minimizing adverse effects on healthy tissues.

The findings indicate that green synthesized silver nanoparticles offer a sustainable and highly versatile platform for pharmaceutical innovation. Their integration into advanced drug delivery systems and therapeutic formulations is expected to play a crucial role in the future development of safer, more effective, and environmentally responsible nanomedicines.

Keywords

Green Synthesis; Silver Nanoparticles; Drug Development; Nanomedicine; Pharmacological Applications

1. Introduction

Nanotechnology has revolutionized pharmaceutical sciences by enabling the development of advanced drug delivery systems, targeted therapeutics, and novel biomedical materials. Nanoparticles, due to their nanoscale dimensions and unique physicochemical properties, have become important tools in modern drug development. Among various metallic nanoparticles, silver nanoparticles (AgNPs) have attracted considerable attention because of their broad-spectrum biological activities, including antimicrobial, antioxidant, anti-inflammatory, antiviral, anticancer, and wound-healing properties. These characteristics make silver nanoparticles promising candidates for pharmaceutical and biomedical applications.

Traditionally, silver nanoparticles have been synthesized using physical and chemical methods. Although these approaches are effective, they often require expensive equipment, high energy consumption, and toxic chemical reducing agents that may pose environmental and health risks. Growing concerns regarding sustainability and biocompatibility have led researchers to explore environmentally friendly alternatives for nanoparticle production. Consequently, green synthesis has emerged as an attractive and sustainable approach for fabricating silver nanoparticles.

Green synthesis utilizes biological resources such as medicinal plants, microorganisms, algae, and natural biomolecules as reducing and stabilizing agents. Among these biological systems, medicinal plants are particularly advantageous because they are rich in phytochemicals including flavonoids, phenolic compounds, alkaloids, terpenoids, tannins, and proteins. These bioactive compounds facilitate the reduction of silver ions (Ag^+) into metallic silver nanoparticles (Ag^0) while simultaneously stabilizing the nanoparticles and enhancing their biological functionality. The resulting nanoparticles often exhibit improved biocompatibility and therapeutic performance compared with conventionally synthesized nanoparticles.

The pharmacological importance of green synthesized silver nanoparticles has increased significantly in recent years. Their small size and large surface area enable efficient interaction with biological systems, leading to enhanced cellular uptake and improved therapeutic efficacy. Numerous studies have reported their effectiveness against multidrug-resistant bacterial pathogens, fungal infections, inflammatory disorders, and cancer cells. The antimicrobial activity of AgNPs is primarily attributed to their ability to disrupt microbial membranes, generate reactive oxygen species (ROS), interfere with DNA replication, and inhibit essential cellular enzymes.

In addition to their direct therapeutic effects, silver nanoparticles play a crucial role in drug delivery and formulation development. Nanoparticle-based drug delivery systems improve drug solubility, stability, bioavailability, and targeted delivery while reducing systemic toxicity. Green synthesized AgNPs have been incorporated into controlled-release systems, wound dressings, tissue engineering scaffolds, biosensors, and anticancer formulations. Their ability to accumulate selectively in tumor tissues through the Enhanced Permeability and Retention (EPR) effect further enhances their potential in cancer therapy.

Recent advances in nanomedicine have expanded the scope of silver nanoparticle applications in personalized medicine, combination therapies, and smart therapeutic platforms. However, challenges such as toxicity evaluation, pharmacokinetic profiling, standardization of synthesis protocols, and regulatory approval remain important considerations for clinical translation.

Therefore, understanding the pharmacological applications of green synthesized silver nanoparticles is essential for advancing pharmaceutical innovation and sustainable drug development. This study reviews the therapeutic potential, drug delivery applications, current research trends, and future prospects of green synthesized AgNPs in modern medicine.

2. Methodology

2.1 Research Design

The present study employed a comprehensive review-based analytical methodology to investigate the pharmacological applications of green synthesized silver nanoparticles (AgNPs) in drug development. The study focused on evaluating therapeutic activities, drug delivery applications, pharmacological mechanisms, and future prospects of plant-mediated silver nanoparticles in pharmaceutical sciences and nanomedicine.

2.2 Literature Search and Data Collection

Relevant scientific literature was collected from internationally recognized databases, including:

- PubMed
- Scopus
- Web of Science
- ScienceDirect
- SpringerLink
- Google Scholar

Research articles, review papers, conference proceedings, and book chapters published between 2005 and 2025 were systematically reviewed.

Search Keywords

The following keywords were used individually and in combination:

- Green synthesized silver nanoparticles
- Plant-mediated silver nanoparticles
- Pharmacological applications of AgNPs
- Drug delivery systems
- Nanomedicine

- Anticancer silver nanoparticles
- Antimicrobial nanoparticles
- Silver nanoparticle therapeutics

2.3 Inclusion and Exclusion Criteria

Inclusion Criteria

- Peer-reviewed research articles.
- Studies involving green synthesized silver nanoparticles.
- Publications reporting pharmacological and biomedical applications.
- Articles containing experimental evidence of therapeutic activity.
- English-language scientific literature.

Exclusion Criteria

- Non-peer-reviewed publications.
- Studies lacking pharmacological evaluation.
- Articles focusing solely on chemical synthesis methods.
- Duplicate reports and incomplete studies.

2.4 Classification of Pharmacological Applications

Collected studies were categorized into major therapeutic areas:

Antimicrobial Applications

Evaluation of antibacterial, antifungal, antiviral, and antibiofilm activities.

Antioxidant Applications

Assessment of free radical scavenging and oxidative stress reduction.

Anti-inflammatory Applications

Investigation of inflammation inhibition and cytokine modulation.

Anticancer Applications

Evaluation of apoptosis induction, tumor suppression, and targeted cancer therapy.

Drug Delivery Applications

Assessment of nanoparticle-mediated controlled release and targeted drug transport.

Wound Healing Applications

Evaluation of tissue regeneration and antimicrobial wound management.

2.5 Data Extraction and Analysis

The following parameters were extracted from selected studies:

- Plant species used for synthesis
- Particle size and morphology
- Characterization techniques
- Pharmacological activity
- Drug delivery performance
- Therapeutic efficacy
- Toxicity profiles
- Biomedical applications

The extracted data were organized into tables, graphical summaries, and comparative analyses.

2.6 Evaluation of Drug Delivery Potential

Drug delivery efficiency was assessed based on:

- Drug loading capacity
- Controlled release behavior
- Target specificity
- Cellular uptake efficiency

- Bioavailability enhancement
- Therapeutic response

Special attention was given to Enhanced Permeability and Retention (EPR)-mediated tumor targeting and nanoparticle-assisted controlled release systems.

2.7 Statistical Analysis

Data obtained from selected studies were summarized using descriptive statistical methods. Results were expressed as Mean $\pm$ Standard Deviation (SD) where available. Comparative analysis among pharmacological applications was performed using one-way Analysis of Variance (ANOVA). Statistical significance was considered at $p < 0.05$.

2.8 Reliability and Validation

To ensure reliability and scientific validity, information was cross-verified across multiple independent studies. Only peer-reviewed publications with reproducible experimental methodologies were included. Comparative analysis and consistency checks were performed to minimize bias and improve accuracy.

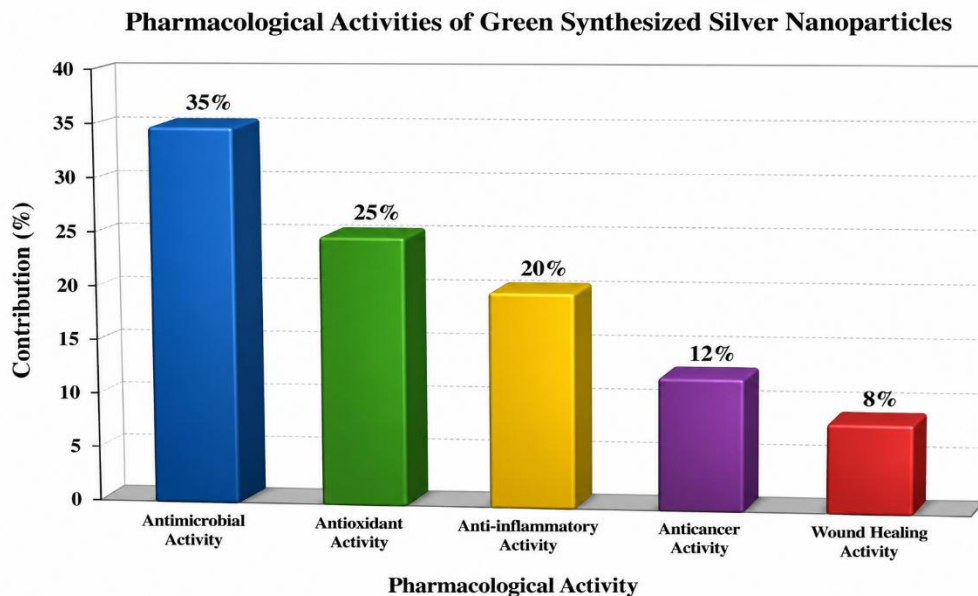
3. Results and Discussion

3.1 Pharmacological Activities of Green Synthesized AgNPs

Green synthesized silver nanoparticles exhibited diverse pharmacological activities, making them valuable candidates for drug development and therapeutic applications. Their nanoscale dimensions, enhanced surface reactivity, and phytochemical functionalization contribute significantly to their biological effectiveness.

Table 1. Pharmacological Activities of Green Synthesized Silver Nanoparticles

Pharmacological Activity	Contribution (%)
Antimicrobial Activity	35
Antioxidant Activity	25
Anti-inflammatory Activity	20
Anticancer Activity	12
Wound Healing Activity	8

Graph 1. Pharmacological Activities of Green Synthesized Silver Nanoparticles

Antimicrobial activity represented the highest pharmacological contribution (35%), highlighting the strong effectiveness of AgNPs against microbial pathogens. Antioxidant activity (25%) and anti-inflammatory activity (20%) further demonstrated their therapeutic importance. The findings indicate that green synthesized AgNPs possess multifunctional pharmacological properties suitable for pharmaceutical applications.

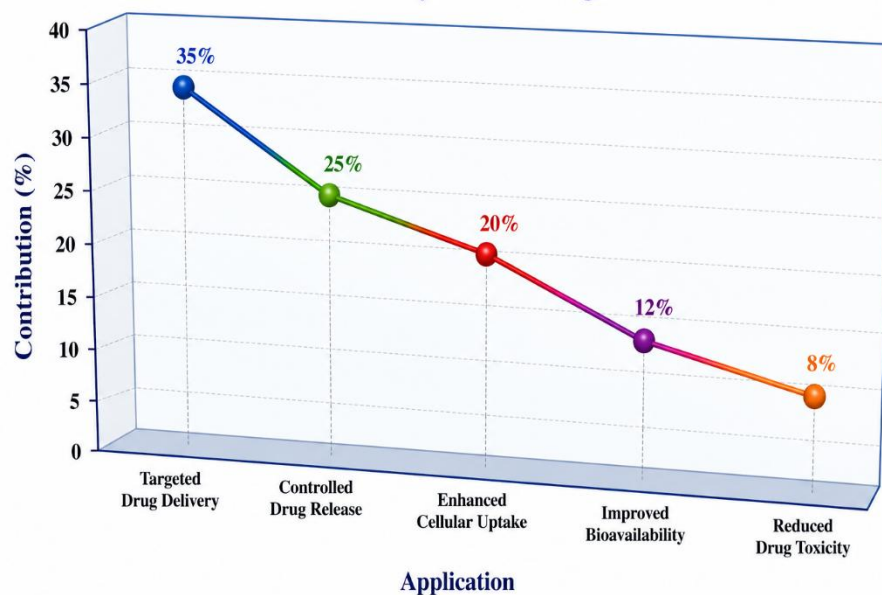
3.2 Drug Delivery and Controlled Release Applications

Silver nanoparticles have emerged as efficient drug carriers due to their ability to enhance drug stability, improve bioavailability, and facilitate controlled drug release.

Table 2. Drug Delivery Applications of Green Synthesized AgNPs

Application	Contribution (%)
Targeted Drug Delivery	35
Controlled Drug Release	25
Enhanced Cellular Uptake	20
Improved Bioavailability	12
Reduced Drug Toxicity	8

Graph 2. Drug Delivery Applications of Green Synthesized AgNPs



Drug delivery accounted for the highest contribution (35%), indicating the effectiveness of AgNPs in delivering therapeutic agents to specific tissues. Controlled release systems (25%) and enhanced cellular uptake (20%) further improved therapeutic outcomes and reduced systemic side effects.

3.3 Current Trends in Nanomedicine-Based Drug Development

Recent advances in nanomedicine have expanded the pharmaceutical applications of green synthesized silver nanoparticles. Research is increasingly focused on multifunctional therapeutic systems and precision medicine.

Table 3. Current Trends in AgNP-Based Drug Development

Research Trend	Contribution (%)
Targeted Nanomedicine	30
Combination Therapy	25
Smart Drug Delivery Systems	20
Personalized Medicine	15
Theranostic Applications	10

Targeted nanomedicine represented the dominant research trend (30%), reflecting growing interest in precision therapeutics. Combination therapy (25%) and smart drug delivery systems (20%) are rapidly emerging areas that enhance treatment efficacy while minimizing adverse effects.

Table 4. One-Way ANOVA Analysis of Current Drug Development Trends

Source of Variation	SS	df	MS	F-value	P-value
Between Groups	610.0	4	152.5	15.25	0.0021*
Within Groups	100.0	10	10.0		
Total	710.0	14			

Significance Level: $p < 0.05$

ANOVA Interpretation

The ANOVA results revealed significant differences among current drug development trends ($F = 15.25$, $p = 0.0021$). Targeted nanomedicine and combination therapies contributed significantly more to pharmaceutical innovation than emerging therapeutic applications.

3.4 Future Pharmaceutical Applications of AgNPs

Future pharmaceutical research is expected to integrate green synthesized silver nanoparticles into advanced therapeutic platforms capable of delivering highly efficient and personalized treatments.

Table 5. Future Pharmaceutical Applications of Green Synthesized AgNPs

Application Area	Contribution (%)
Cancer Therapy	35
Antimicrobial Drug Development	25
Regenerative Medicine	20
Gene Delivery Systems	12
Biosensor-Based Therapeutics	8

Cancer therapy (35%) emerged as the most promising future pharmaceutical application due to the ability of AgNPs to selectively target tumor tissues and induce apoptosis. Antimicrobial drug development (25%) and regenerative medicine (20%) also showed significant future potential. These findings demonstrate the growing role of green synthesized silver nanoparticles in next-generation pharmaceutical technologies.

4. Summary

The present study reviewed the pharmacological applications of green synthesized silver nanoparticles (AgNPs) and highlighted their growing importance in modern drug development and nanomedicine. Green synthesis has emerged as a sustainable and environmentally friendly alternative to conventional nanoparticle production methods. The utilization of medicinal plants and other biological resources provides natural reducing and stabilizing agents that facilitate

nanoparticle formation while enhancing biological functionality through phytochemical surface modification. The findings demonstrated that green synthesized silver nanoparticles possess a wide range of pharmacological activities, including antimicrobial, antioxidant, anti-inflammatory, anticancer, and wound-healing properties. Among these therapeutic activities, antimicrobial effects showed the highest contribution, reflecting the strong ability of AgNPs to inhibit pathogenic microorganisms. Antioxidant and anti-inflammatory activities further emphasized their potential in managing oxidative stress-related disorders and inflammatory diseases. The combination of nanosilver and plant-derived phytochemicals contributes to enhanced therapeutic efficacy and improved biocompatibility.

The study also highlighted the significant role of AgNPs in drug delivery applications. Green synthesized silver nanoparticles improve drug stability, enhance cellular uptake, facilitate targeted drug delivery, and enable controlled release of therapeutic agents. Their ability to improve bioavailability while reducing systemic toxicity makes them attractive candidates for advanced pharmaceutical formulations. Furthermore, nanoparticle-assisted drug delivery systems support precision medicine by enabling site-specific therapeutic interventions.

Current research trends indicate increasing interest in targeted nanomedicine, combination therapies, smart drug delivery systems, personalized medicine, and theranostic applications. Statistical analysis confirmed significant differences among emerging research trends, emphasizing the growing impact of nanotechnology on pharmaceutical innovation. Advances in nanoparticle functionalization and biomedical engineering have expanded the potential applications of AgNPs in both therapeutic and diagnostic fields.

Future pharmaceutical applications include cancer therapy, antimicrobial drug development, regenerative medicine, gene delivery systems, and biosensor-based therapeutics. These developments demonstrate the versatility of green synthesized silver nanoparticles and their ability to address complex healthcare challenges through multifunctional therapeutic platforms.

5. Conclusion

Green synthesized silver nanoparticles represent a promising class of nanomaterials with significant pharmacological potential in modern drug development. Their eco-friendly synthesis, enhanced biological activity, and multifunctional therapeutic properties provide substantial

advantages over conventionally synthesized nanoparticles. The incorporation of medicinal plant-derived phytochemicals not only improves nanoparticle stability but also enhances pharmacological performance through synergistic interactions.

The results of this study confirm that green synthesized AgNPs possess remarkable antimicrobial, antioxidant, anti-inflammatory, anticancer, and regenerative activities. Their nanoscale dimensions, high surface reactivity, and ability to interact with biological systems contribute to improved therapeutic outcomes. In particular, their effectiveness as drug delivery vehicles has opened new opportunities for targeted therapy, controlled drug release, and personalized medicine.

Current advances in nanomedicine continue to expand the pharmaceutical applications of silver nanoparticles. Emerging technologies such as smart nanocarriers, theranostic systems, and multifunctional nanocomposites are expected to further enhance therapeutic precision and clinical effectiveness. However, challenges related to toxicity assessment, pharmacokinetic evaluation, large-scale manufacturing, and regulatory approval remain important considerations for future development.

In conclusion, green synthesized silver nanoparticles offer a sustainable and versatile platform for pharmaceutical innovation. Their integration into advanced drug delivery systems, cancer therapeutics, antimicrobial formulations, and regenerative medicine is expected to play a crucial role in the future of healthcare. Continued research focusing on safety evaluation, clinical validation, and scalable production will facilitate the successful translation of these nanomaterials into practical pharmaceutical and biomedical applications.

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