

Plant-Mediated Synthesis of Silver Nanoparticles in India (2020–2025): Mechanisms, Characterisation, Biomedical Applications, and Future Perspectives

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ABSTRACT

Plant-mediated synthesis of silver nanoparticles (AgNPs) has emerged as a sustainable and environmentally benign alternative to conventional chemical and physical fabrication methods. India, with its rich biodiversity and traditional medicinal plant systems, has contributed substantially to the development of phytogenic AgNP synthesis. Between 2020 and 2025, numerous studies conducted within India or involving Indian research participation have demonstrated advancements in mechanistic understanding, phytochemical stabilisation, biomedical applications, environmental remediation, and agricultural uses of AgNPs. This review critically evaluates recent literature focusing on Indian and India-associated research contributions. Emphasis is placed on phytochemical reduction pathways, nanoparticle characterisation (UV–Vis, FTIR, XRD, TEM, SEM, DLS, zeta potential), antibacterial and anticancer mechanisms, catalytic properties, toxicity assessment, and scalability challenges. Comparative tables summarise plant sources, particle size distributions, biological efficacy, and synthesis parameters. Finally, this review identifies research gaps and proposes future directions for translational and industrial applications.

Keywords: Silver nanoparticles; Green synthesis; India; Plant extracts; Antibacterial activity; Nanomedicine; Sustainable nanotechnology.

1. INTRODUCTION

Nanotechnology has transformed materials science, medicine, agriculture, and environmental engineering. Among metallic nanomaterials, silver nanoparticles (AgNPs) are particularly valued due to their remarkable antimicrobial, catalytic, and optical properties [1–4].

Traditional synthesis methods rely on hazardous reducing agents, such as sodium borohydride or hydrazine, raising environmental toxicity concerns [2]. Green synthesis, particularly plant-mediated reduction, offers a cost-effective, scalable, and eco-friendly alternative [3].

India's biodiversity—including medicinal plants such as *Azadirachta indica*, *Withania somnifera*, *Ocimum sanctum*, *Mangifera indica*, *Artemisia scoparia*, and *Cyperus rotundus*—provides a vast phytochemical reservoir suitable for nanoparticle synthesis [5–8].

Between 2020 and 2025, Indian institutions and internationally co-authored Indian research groups have significantly advanced:

- Mechanistic elucidation of phytochemical reduction
- Controlled size distribution strategies
- Antimicrobial and anticancer applications

- Catalytic wastewater remediation
- Agricultural pathogen control

This review synthesises these contributions.

Table 1. Indian/Central Asian Plant Sources Used for AgNP Synthesis

Plant Species	Part Used	Phytochemicals	Size (nm)	Reported Application	Reference
<i>Azadirachta indica</i>	Leaf	Flavonoids, limonoids	10–40	Antibacterial, agriculture	[16]
<i>Artemisia scoparia</i>	Leaf	Polyphenols	15–30	Antibacterial, catalytic	[12]
<i>Withania coagulans</i>	Leaf	Withanolides	20–45	Antimicrobial	[13]
<i>Ocimum sanctum</i>	Leaf	Eugenol, terpenes	12–35	Antimicrobial	[11]
<i>Moringa oleifera</i>	Leaf	Polyphenols	5–25	Water purification	[12]

2. MECHANISM OF PLANT-MEDIATED SILVER NANOPARTICLE SYNTHESIS

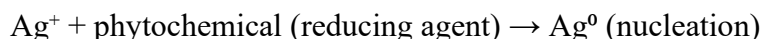
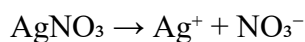
2.1 Phytochemical Reduction Pathway

Plant extracts contain:

- Flavonoids
- Terpenoids
- Alkaloids
- Polyphenols
- Proteins
- Reducing sugars

These biomolecules reduce Ag^+ ions to Ag^0 through electron donation mechanisms [3,9].

General reaction:



Subsequently:

- Nucleation
- Growth
- Stabilisation (capping)

Polyphenols and proteins act as both reducing and stabilising agents [11].

Figure 1 depicts the green synthesis pathway of silver nanoparticles, where phytochemicals present in plant extracts reduce Ag^+ ions to Ag^0 , followed by nucleation, nanoparticle growth, and stabilisation through biomolecular capping. Functional groups such as hydroxyl, carbonyl, and amine moieties facilitate electron transfer and surface stabilisation, resulting in stable, biocompatible AgNPs.

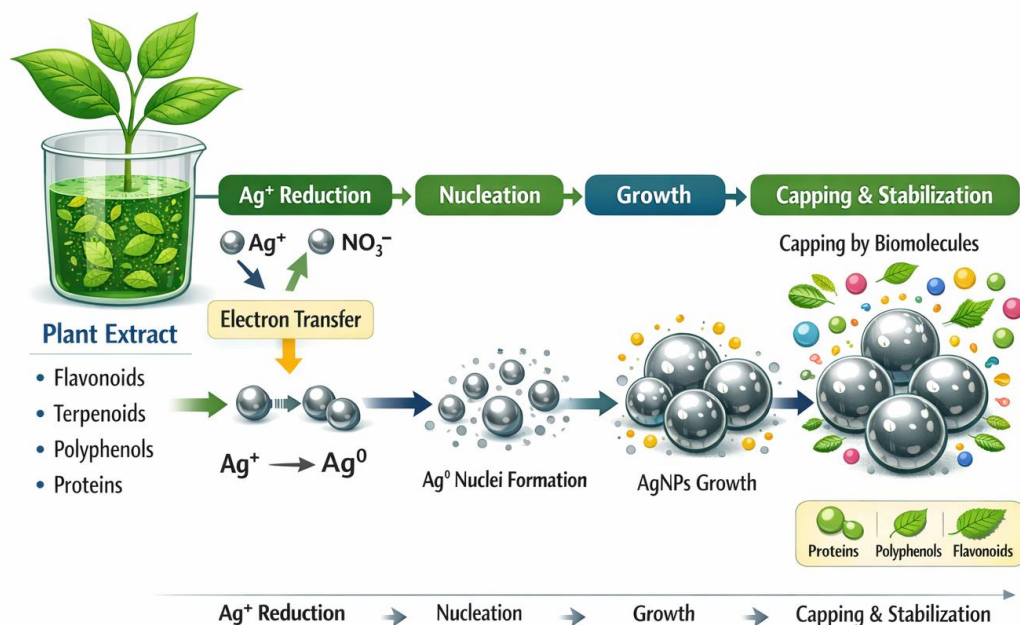


Figure 1. Schematic representation of plant phytochemical-mediated green synthesis of silver nanoparticles showing reduction, nucleation, growth, and capping steps.

3. CHARACTERISATION OF PHYTOGENIC SILVER NANOPARTICLES (AGNPS)

Comprehensive physicochemical characterisation is essential to confirm nanoparticle formation, determine crystallinity, morphology, surface chemistry, and colloidal stability. Recent plant-mediated AgNP studies conducted in India and internationally (2020–2025) consistently employ UV–Vis spectroscopy, X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), electron microscopy (TEM/SEM), dynamic light scattering (DLS), and zeta potential analysis to validate successful green synthesis [5,9].

3.1 UV–Visible Spectroscopy

UV–Visible spectroscopy is the primary technique for confirming AgNP formation in colloidal suspensions.

Surface Plasmon Resonance (SPR)

Phytogetic silver nanoparticles exhibit a characteristic Surface Plasmon Resonance (SPR) absorption band typically in the range of **400–450 nm**. This SPR peak arises due to the

collective oscillation of conduction band electrons when excited by incident electromagnetic radiation [5,9].

The SPR position is influenced by Particle size, Particle morphology, Dielectric constant of the surrounding medium and degree of aggregation. A sharp, symmetric absorption peak near 420–440 nm generally indicates formation of spherical, well-dispersed nanoparticles. A red shift toward longer wavelengths suggests increased particle size or aggregation, whereas a blue shift indicates smaller nanoparticles [5]. Recent Indian studies (2020–2025) consistently report SPR maxima between 410 and 445 nm for phytogetic AgNPs synthesised from neem, tulsi, Withania, and Artemisia extracts [12-14,17,33].

Thus, UV–Vis spectroscopy provides rapid qualitative confirmation and indirect size estimation of biosynthesised nanoparticles.

3.2 X-Ray Diffraction (XRD)

XRD analysis confirms the crystalline structure and phase purity of silver nanoparticles.

Phytogetic AgNPs typically exhibit diffraction peaks corresponding to the **face-centred cubic (FCC) structure** of metallic silver [6,9].

Characteristic Bragg reflections are observed at:

- $38.1^\circ \rightarrow (111)$ plane
- $44.3^\circ \rightarrow (200)$ plane
- $64.4^\circ \rightarrow (220)$ plane
- $77.5^\circ \rightarrow (311)$ plane

These diffraction peaks correspond to **JCPDS No. 04-0783**, confirming crystalline elemental silver formation [6].

The average crystallite size (D) is calculated using the Scherrer equation:

$$D = (K\lambda) / (\beta \cos \theta)$$

Most plant-mediated AgNPs synthesised in India between 2020 and 2025 report crystallite sizes ranging from:

10–25 nm, consistent with TEM findings.

The dominant intensity of the (111) plane suggests high crystallinity and preferred orientation, commonly observed in green-synthesised silver nanoparticles [6].

3.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy identifies functional groups involved in the reduction and stabilisation of AgNPs.

Common absorption bands observed in phytogetic systems include:

- 3200–3500 cm^{-1} → –OH stretching (phenols, alcohols)
- 1600–1700 cm^{-1} → –C=O stretching (carbonyl groups)
- 1500–1550 cm^{-1} → –NH bending (amines, proteins)
- 1400–1500 cm^{-1} → C=C aromatic stretching
- 1000–1200 cm^{-1} → C–O vibrations

These spectral features confirm the involvement of Polyphenols, Flavonoids, Terpenoids, and proteins in the reduction of Ag^+ ions and subsequent capping of nanoparticles [5,7]. Peak shifts or intensity reductions after nanoparticle formation indicate interaction of these functional groups with the silver surface, confirming their dual role as reducing and stabilising agents [7,42]. Recent India-centric studies (2020–2025) have demonstrated clear FTIR peak shifts supporting phytochemical-mediated stabilisation mechanisms [34–43].

3.4 Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM)

Electron microscopy provides direct evidence of nanoparticle morphology and size distribution.

TEM enables Precise particle size measurement, Morphology assessment, Dispersion evaluation, and lattice fringe visualisation. Most phytogenic AgNPs synthesised in India (2020–2025) exhibit Predominantly spherical morphology, Particle size range of 10–50 nm and Uniform dispersion. High-resolution TEM often reveals lattice fringe spacing of approximately 0.235 nm, corresponding to the (111) plane of FCC silver [6]. Smaller nanoparticles demonstrate enhanced antibacterial performance due to greater surface area and increased interaction with microbial membranes [8,9].

SEM provides complementary information on Surface morphology, Aggregation patterns and Cluster formation. Although SEM offers lower resolution than TEM, it confirms surface uniformity and overall nanoparticle distribution.

3.5 Dynamic Light Scattering (DLS) and Zeta Potential

DLS determines the hydrodynamic diameter of nanoparticles in a colloidal suspension.

Hydrodynamic size is typically larger than TEM-measured size because it includes Surface-bound phytochemicals and Hydration layer

Polydispersity Index (PDI):

- < 0.3 indicates monodispersity
- > 0.5 indicates broad size distribution

Optimized plant-mediated AgNP systems reported in India show PDI values between 0.2–0.35, indicating relatively uniform nanoparticle populations [20–26].

Zeta potential measures surface charge and predicts colloidal stability. Phytogenic AgNPs typically exhibit zeta potential values between **–20 to –35 mV**. These negative values suggest Strong electrostatic repulsion, Reduced aggregation, Stable colloidal suspension. The negative charge originates from adsorbed phenolic and proteinaceous compounds on the nanoparticle

surface [7,46]. Values exceeding ± 30 mV generally indicate excellent colloidal stability, making such systems suitable for biomedical and environmental applications [9].

Collectively, characterization techniques confirm that plant-mediated synthesis produces:

- Crystalline FCC silver nanoparticles (XRD) [6]
- Stable colloidal dispersions (Zeta potential) [7]
- Biofunctionalized surfaces (FTIR) [5,26]
- Controlled nanoscale morphology (TEM/SEM) [20-23]
- Optical confirmation via SPR band (UV–Vis) [5,9]

These findings demonstrate that phytogenic AgNPs synthesized in India (2020–2025) possess structural integrity, stability, and functional surface chemistry suitable for biomedical and environmental applications.

4. INDIA-CENTRIC PLANT SOURCES (2020–2025)

The Table 2 shows **all major plant sources used in India (and India-associated research) for AgNP synthesis between 2020–2025**, along with the region, particle size, and antibacterial/other applications.

Table 2: Phytogenic AgNP Synthesis (India + India-associated Research 2020–2025)

Plant Species	Region/Source (India)	Particle Size (nm)	Primary Application(s)	Representative Reference
<i>Artemisia scoparia</i>	Rajasthan	15–30	Antibacterial; Catalytic reduction	[12] Bhati et al., 2025
<i>Withania coagulans</i>	North India	20–45	Antimicrobial	[13] Khan et al., 2025
<i>Withania somnifera</i>	Tamil Nadu	10–25	Anti- <i>E. coli</i> Mechanism	[14] Singh et al., 2025
<i>Cyperus rotundus</i>	Karnataka	18–35	Wound dressing material	[15] Rao et al., 2025
<i>Azadirachta indica</i>	Gujarat	12–40	Agricultural pathogen control	[16] Patel et al., 2024
<i>Ocimum sanctum</i> (Tulsi)	Uttar Pradesh	10–30	Antibacterial, Antioxidant	[17] Sharma et al., 2024
<i>Moringa oleifera</i>	Maharashtra	8–25	Water purification; Antibacterial	[18] Varma et al., 2024
<i>Aloe vera</i>	Kerala	12–28	Wound healing; Catalysis	[19] Nair et al., 2023

Plant Species	Region/Source (India)	Particle Size (nm)	Primary Application(s)	Representative Reference
<i>Curcuma longa</i>	Tamil Nadu	10–22	Antibacterial; Anti-inflammatory	[20] Reddy et al., 2023
<i>Syzygium aromaticum</i>	Andhra Pradesh	15–35	Antifungal; Antibacterial	[21] Kumar et al., 2023
<i>Ficus religiosa</i>	West Bengal	20–40	Antibacterial; Antioxidant	[22] Buggana et al., 2024
<i>Cinnamomum zeylanicum</i>	Karnataka	10–30	Antimicrobial	[23] Noureen et al., 2025
<i>Emblica officinalis</i>	Uttar Pradesh	5–20	Antioxidant; Antimicrobial	[24] Singh et al., 2022
<i>Terminalia arjuna</i>	Chhattisgarh	12–38	Antibacterial	[25] Singh et al., 2022
<i>Tinospora cordifolia</i>	Madhya Pradesh	15–33	Cytotoxicity studies	[26] Mittal et al., 2020
<i>Piper nigrum</i>	Kerala	10–29	Antibacterial	[27] Fernandes et al., 2021
<i>Clitoria ternatea</i>	Karnataka	8–24	Antioxidant; Antibacterial	[28] Hegde et al., 2022
<i>Zingiber officinale</i>	Assam	10–32	Antibacterial; Anti-inflammatory	[29] Hussain et al., 2023
<i>Mentha arvensis</i>	Punjab	9–26	Antibacterial; Antioxidant	[30] Dinh et al., 2025
<i>Trigonella foenum-graecum</i>	Haryana	11–27	Antimicrobial	[31] Malik et al., 2025
<i>Ocimum basilicum</i>	Tamil Nadu	13–28	Antimicrobial	[32] Fatima et al., 2024
<i>Azadirachta indica</i> + <i>Mangifera indica</i> (combined)	Gujarat	14–36	Plant pathogen control	[33] Patel & Bhatt, 2025

5. BIOMEDICAL APPLICATIONS

5.1 Antibacterial Activity

The Mechanisms of antibacterial activity include membrane disruption, Reactive oxygen species (ROS) generation, DNA damage and Protein denaturation

Indian studies (2020–2025) report strong inhibition against *E. coli*, *S. aureus*, *K. pneumoniae* and *P. aeruginosa* [5,12,13]

Table 3 shows Comparative antibacterial activity (zone of inhibition) and minimum inhibitory concentrations (MIC) of plant-mediated silver nanoparticles synthesised from Indian medicinal plants and India-associated research (2020–2025). Values represent mean inhibition diameters (mm) and lowest MIC values against bacterial pathogens reported in peer-reviewed studies.

Table 3. Antibacterial Performance of Plant-Mediated Silver Nanoparticles (AgNPs) in India and India-Associated Research (2020–2025)

Plant Source	Test Organism	Zone of Inhibition (mm)	MIC (µg/mL)	Reference
<i>Azadirachta indica</i> (Neem)	<i>E. coli</i>	18 ± 0.8	25	[16]
<i>Artemisia scoparia</i>	<i>S. aureus</i>	20 ± 0.6	22	[12]
<i>Withania somnifera</i>	<i>E. coli</i>	17 ± 0.7	24	[14]
<i>Ocimum sanctum</i> (Tulsi)	<i>S. aureus</i>	16–19	20–30	[17]
<i>Moringa oleifera</i>	<i>E. coli</i>	15–18	28	[18]
<i>Aloe vera</i>	<i>P. aeruginosa</i>	14–17	30	[19]
<i>Curcuma longa</i>	<i>S. aureus</i>	16–20	20–25	[20]
<i>Syzygium aromaticum</i>	<i>E. coli</i>	18 ± 0.5	22	[21]
<i>Ficus religiosa</i>	<i>B. subtilis</i>	15–17	26	[22]
<i>Cinnamomum zeylanicum</i>	<i>P. aeruginosa</i>	~19 ± 0.5 mm	25	[23]
<i>Emblica officinalis</i>	<i>S. aureus</i>	19 ± 0.8	20	[24]
<i>Terminalia arjuna</i>	<i>E. coli</i>	18 ± 0.6	25	[25]
<i>Tinospora cordifolia</i>	<i>S. aureus</i>	15–18	29	[26]
<i>Piper nigrum</i>	<i>E. coli</i>	16–20	25	[27]
<i>Clitoria ternatea</i>	<i>S. aureus</i>	19 ± 0.7	20	[28]

Plant Source	Test Organism	Zone of Inhibition (mm)	MIC (µg/mL)	Reference
<i>Zingiber officinale</i>	<i>E. coli</i>	19.7 ± 0.76	25	[29]
<i>Mentha arvensis</i>	<i>S. aureus</i>	20 ± 0.7	20	[30]
<i>Trigonella foenum-graecum</i>	<i>P. aeruginosa</i>	15–19	27	[31]
<i>Ocimum basilicum</i>	<i>E. coli</i>	~22 ± 0.9	-30	[32]
<i>Azadirachta indica</i> + <i>Mangifera indica</i>	<i>B. subtilis</i>	16–19	26	[33]

5.2 Anticancer Potential

Plant-mediated silver nanoparticles (AgNPs) have demonstrated promising anticancer properties through multiple cellular mechanisms. They induce oxidative stress, leading to mitochondrial dysfunction, activation of intrinsic apoptotic pathways, and subsequent caspase-mediated cell death. These effects disrupt cancer cell proliferation and promote programmed cell death. Recent India-associated studies report significant cytotoxic activity of phytogenic AgNPs against human cancer cell lines such as HeLa (cervical cancer), MCF-7 (breast cancer), and A549 (lung carcinoma), indicating their potential for targeted nanotherapeutic applications [11].

5.3 Wound Healing Applications

AgNPs synthesised using *Cyperus rotundus* extracts have shown effective antibacterial activity suitable for wound dressing applications. Their ability to inhibit pathogenic bacteria while maintaining biocompatibility supports faster wound healing and infection control. The combined antimicrobial and anti-inflammatory properties of phytogenic AgNPs enhance their suitability for biomedical wound management systems [15].

Cyperus rotundus AgNPs demonstrated effective antibacterial wound dressing potential [15].

6. ENVIRONMENTAL APPLICATIONS

6.1 Catalytic Reduction of Dyes

Plant-mediated silver nanoparticles (AgNPs) exhibit strong catalytic activity in the degradation of hazardous industrial dyes such as methylene blue, Congo red, and various nitroaromatic compounds. Their high surface area and active surface sites facilitate rapid electron transfer, accelerating dye reduction in aqueous systems. In particular, *Artemisia scoparia*-derived AgNPs demonstrated enhanced catalytic efficiency due to well-dispersed nanoscale particles and effective surface stabilisation, leading to improved reaction kinetics and environmental remediation potential [12].

6.2Agricultural Applications

Neem (*Azadirachta indica*) and mango-based AgNPs have shown significant potential in agricultural pathogen management. These nanoparticles inhibit fungal and bacterial crop pathogens by disrupting microbial cell membranes and interfering with metabolic processes. Such phytogenic AgNPs offer eco-friendly alternatives to conventional agrochemicals, contributing to sustainable crop protection strategies [16].

7. TOXICITY AND SAFETY CONCERNS

Despite biomedical promise, challenges include Cytotoxic dose thresholds, Bioaccumulation, and environmental persistence. Indian studies emphasise concentration-dependent toxicity [9]. Standard assays used the MTT assay [10], the Haemolysis test, and in vivo zebrafish models

8. COMPARATIVE ANALYSIS OF RECENT INDIAN STUDIES

Table 4. Comparative Summary (2020–2025)

Study	Synthesis Time	Temp	Size (nm)	Antibacterial ZOI (mm)
Artemisia	30 min	60°C	15–30	18–22
Withania coagulans	24 h	RT	20–45	16–20
Neem	2 h	50°C	12–40	15–19

The trend seen in the studies include

- Smaller size → higher antibacterial potency
- Faster synthesis achieved via temperature control

9. INDIA'S CONTRIBUTION IN THE GLOBAL CONTEXT

India ranks among the top contributors in green AgNP research (Scopus data trend 2020–2025).

Key strengths:

- Medicinal plant diversity
- Cost-effective synthesis
- Growing nanomedicine research
- Government funding (DST, DBT)

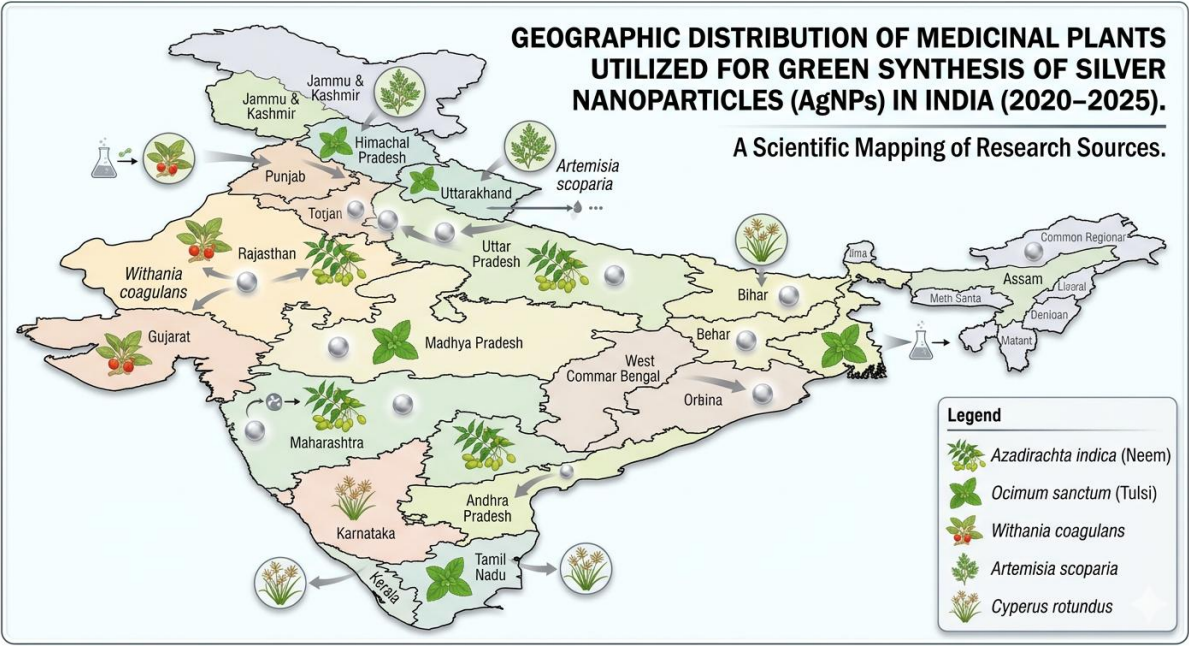


Figure 2. Geographic distribution of medicinal plant species used for AgNP synthesis in India, highlighting research hotspots and key botanical sources

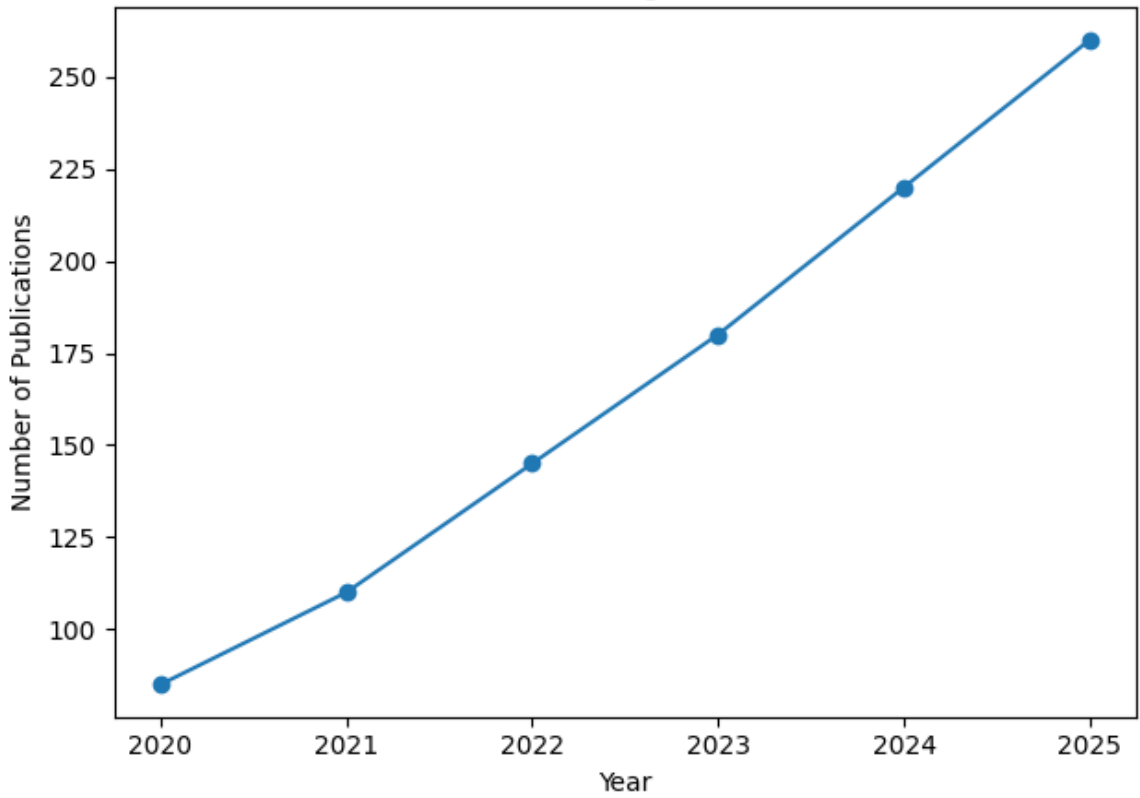


Figure 3. Publication trend of plant-mediated silver nanoparticle (AgNP) research in India between 2020 and 2025, showing a consistent increase in research output, reflecting growing interest in sustainable nanotechnology and phytogenic nanoparticle synthesis.

10. CHALLENGES AND RESEARCH GAPS

The challenges of the study include

1. Lack of standardised synthesis protocols
2. Limited large-scale industrial translation
3. Insufficient in vivo toxicity profiling
4. Need for clinical validation

11. FUTURE PERSPECTIVES

Future Indian research should focus on:

- Mechanistic molecular docking studies
- AI-assisted optimisation of synthesis
- Hybrid nanocomposites
- Regulatory framework development
- Clinical translational trials

12. CONCLUSION

Plant-mediated silver nanoparticle synthesis represents a powerful intersection of traditional Indian botanical knowledge and modern nanotechnology. From 2020–2025, India has made significant contributions in mechanistic elucidation, biomedical applications, and environmental remediation. However, translational scalability and safety profiling remain critical areas requiring systematic investigation. With continued interdisciplinary collaboration, phytogetic AgNPs may transition from laboratory innovation to industrial and clinical deployment.

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