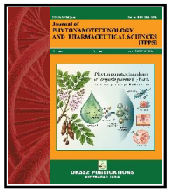
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Phytofabricated nanoparticles from *Azadirachta indica* A. Juss. extract: Antioxidant, antimicrobial, and anti-inflammatory categorization

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Abstract

Phytonanotechnology, the convergence of green chemistry, nanotechnology and plant biotechnology, offers a sustainable route for fabricating functional nanomaterials without hazardous reagents or energy intensive processing. *Azadirachta indica* A. Juss., a fast-growing evergreen tree of the Meliaceae family long valued in Ayurvedic medicine, has emerged as a versatile biological platform for such synthesis due to its exceptional phytochemical richness. Its leaves, seeds, bark, flowers, gum, fruit peel and roots contain limonoids (azadirachtin, nimbin, nimbolide, salannin, gedunin), flavonoids (quercetin, kaempferol, rutin), phenolic acids, terpenoids, alkaloids, proteins and polysaccharides that act as reducing, capping and stabilizing agents during nanoparticle formation. This review synthesizes current evidence on *A. indica* mediated green synthesis of metallic and metal oxide nanoparticles, covering the phytochemical basis of biosynthesis; the mechanistic stages of extract preparation, reduction, nucleation and stabilization, and the influence of pH, temperature, precursor concentration and extract-to-precursor ratio on particle size and morphology. *A. indica* derived silver, gold, zinc oxide, copper oxide, iron oxide, magnesium oxide and selenium nanoparticles are examined with respect to synthesis routes, physicochemical characterization (UV-Vis, FTIR, XRD, SEM/TEM, DLS, zeta potential) and biological activities. The review further discusses emerging biomedical applications, including targeted drug delivery, cancer therapy, antimicrobial coatings, wound healing, tissue engineering, diagnostic imaging, gene and vaccine delivery, dentistry and ophthalmic therapeutics, alongside established agricultural and antimicrobial uses stemming from *A. indica's* pesticidal reputation. Persistent challenges synthesis standardization, batch-to-batch reproducibility, scale-up, long-term biosafety and regulatory clarity are outlined, along with future directions involving AI-assisted optimization, multi-omics-guided mechanistic studies and precision nanomedicine.

1. Introduction

Nanotechnology has become one of the most transformative scientific disciplines of the twenty-first century, enabling unprecedented advances in medicine, agriculture, environmental remediation and materials science. Nanoparticles typically ranging from 1 to 100 nm possess a high surface area to volume ratio, tuneable optical and catalytic properties and improved biological interactions that distinguish them from their bulk counterparts, driving the development of advanced drug delivery systems, biosensors, antimicrobial agents and diagnostic platforms.

Conventional nanoparticle synthesis, however, relies heavily on physical and chemical routes that demand high energy input, costly instrumentation and hazardous reducing agents such as sodium borohydride, hydrazine hydrate and organic solvents, raising environmental and health concerns. This has driven a paradigm shift toward green nanotechnology, which integrates green chemistry principles with nanoscience to fabricate nanomaterials using biomolecules derived from bacteria, fungi, algae and, most prominently, higher plants. Plant mediated synthesis is inexpensive, scalable, does not require aseptic culture conditions and yields nanoparticles coated with bioactive phytochemicals that enhance biocompatibility and therapeutic performance.

Among medicinal plants explored for nanoparticle biosynthesis, *A. indica*, a member of the family Meliaceae, is one of the most extensively investigated owing to its extraordinary phytochemical diversity and centuries of documented use in traditional Ayurvedic, Unani and folk medicine. Commonly called the village pharmacy or nature's drugstore, *A. indica* is a fast-growing, drought tolerant evergreen tree native to the Indian subcontinent and now naturalized across South and Southeast Asia, Africa and parts of the Americas. Almost every part of the plant, including leaves, bark, seeds, flowers, fruit pulp, gum and roots, is used in traditional remedies, pest control and cosmetics, and each part carries a distinct phytochemical fingerprint that can be exploited for nanoparticle fabrication.

The reducing capacity of *A. indica* extracts stems primarily from its limonoid-rich chemistry. Azadirachtin, nimbin, nimbolide, salannin and gedunin, together with flavonoids such as quercetin and kaempferol, phenolic acids, tannins, proteins and reducing sugars, donate electrons that convert dissolved metal ions into zero valent

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nanoparticles while simultaneously adsorbing onto particle surfaces to prevent aggregation. Because *A. indica* is already renowned for antimicrobial, antifeedant, anti-inflammatory, antioxidant and anticancer activity, nanoparticles synthesized in its presence frequently inherit or amplify these properties, producing multifunctional nanomaterials suited to biomedical, agricultural and environmental applications.

Despite an expanding body of literature, current knowledge on *A. indica* mediated nanoparticle synthesis remains scattered across chemistry, pharmacology, agriculture and materials-science journals, with few reviews integrating the phytochemical basis, synthesis mechanisms, characterization approaches and biomedical translation into a single account. This review therefore aims to summarize the phytochemical composition of *A. indica* relevant to nanoparticle biosynthesis, describe the mechanistic stages of *A. indica* mediated green synthesis and the reaction parameters that govern nanoparticle quality, critically evaluate the major classes of *A. indica* derived metallic and metal oxide nanoparticles and their characterization, discuss emerging and established biomedical and agricultural applications, and outline the translational challenges and future directions for this field.

2. Botanical overview of *A. indica*

A. indica, commonly known as *A. indica*, margosa or the miracle tree, belongs to the monogeneric poor family Meliaceae within the order Sapindales. Taxonomically it is classified under Kingdom Plantae, Division Magnoliophyta, Class Magnoliopsida, Order Sapindales, Family Meliaceae. The species is native to the Indian subcontinent and parts of Southeast Asia and has since been widely introduced across Africa, the Middle East, Australia and the Americas because of its drought tolerance, rapid growth and adaptability to poor and marginal soils.

A. indica is a medium to large evergreen tree bearing pinnate leaves, small white fragrant flowers and olive-like drupaceous fruits. Its close relationship with other Meliaceae members such as *M. azedarach* explains the shared abundance of limonoids (tetranortriterpenoids), a chemically distinctive class of bitter principles responsible for much of the plant's antifeedant, antimicrobial and anticancer bioactivity, and a key driver of its utility in green nanoparticle synthesis.

3. Phytochemical profile of *A. indica*

More than 140 bioactive compounds have been reported across the different organs of *A. indica*, encompassing limonoids, flavonoids, phenolic acids, terpenoids, alkaloids, proteins and polysaccharides. These phytochemicals govern nanoparticle nucleation, crystal growth, morphology and stability while simultaneously imparting antimicrobial, antioxidant and anticancer functionality to the resulting nanomaterials (Table 1 and Figure 1).

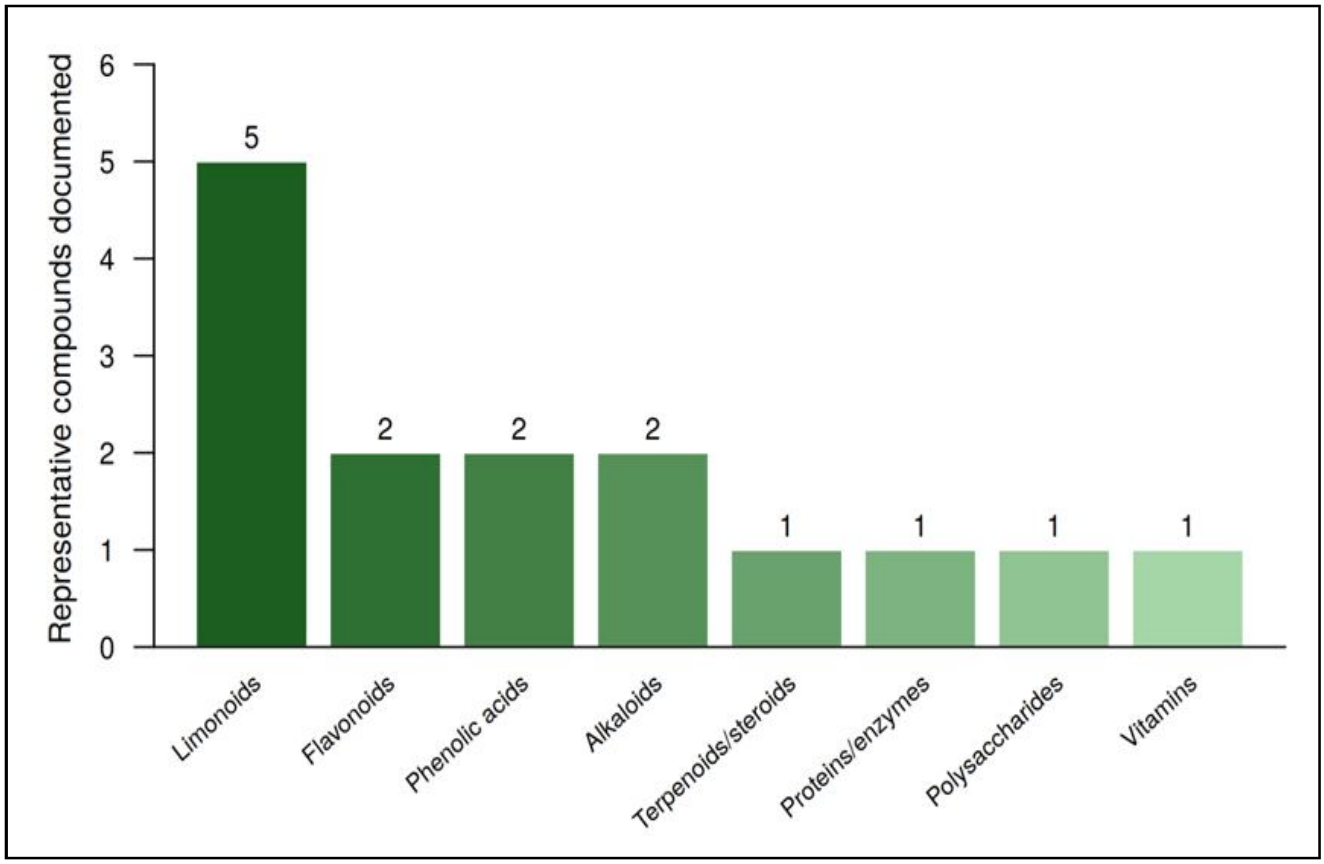


Figure 1: Number of representative bioactive compounds documented per phytochemical class implicated in *A. indica* mediated nanoparticle reduction and capping.

3.1 Limonoids (tetranortriterpenoids)

Limonoids are the signature phytochemicals of *A. indica* and include azadirachtin, nimbin, nimbolide, salannin, gedunin, nimbidin, nimbidol and related derivatives. Their multiple oxygenated functional groups (hydroxyl, carbonyl, epoxide) enable electron donation to metal ions during reduction while also chelating nanoparticle surfaces, contributing antimicrobial, antifeedant, anti-inflammatory and anticancer bioactivity to the phytochemical corona.

3.2 Flavonoids and phenolic acids

Quercetin and kaempferol, two polyphenolic flavonoids abundant in fresh *A. indica* leaf, are well documented for antifungal and antibacterial activity and function as efficient reducing and capping agents. Gallic acid, chlorogenic acid and related phenolic acids further contribute to metal-ion reduction and free-radical scavenging.

3.3 Terpenoids and steroids

Beta-sitosterol and other triterpenes and steroids present in *A. indica* leaves and bark act as hydrophobic stabilizing agents during nanoparticle formation and contribute anti-inflammatory and antimicrobial properties to the final nanomaterial.

3.4 Alkaloids, tannins and saponins

Nimbidin, nimbiol and related alkaloidal and tannin constituents have been detected in aqueous *A. indica* leaf extracts through qualitative phytochemical screening and are implicated in nanoparticle surface stabilization and antimicrobial performance.

3.5 Proteins and polysaccharides

Seed and gum proteins, enzymes and water-soluble carbohydrates present in *A. indica* extracts adsorb onto nanoparticle surfaces, providing steric stabilization, improved colloidal dispersity and enhanced biocompatibility.

3.6 Vitamins and organic acids

Ascorbic acid present in *A. indica* tissues acts as an auxiliary reducing agent, accelerating metal-ion reduction and contributing to the antioxidant character of the resulting nanoparticles.

Table 1: Major phytochemical classes in *A. indica* and their role in nanoparticle biosynthesis and biomedical relevance

Phytochemical class	Representative compounds	Role in nanoparticle synthesis	Biomedical relevance
Limonoids	Azadirachtin, nimbin, nimbolide, salannin, gedunin	Reduction and capping	Antimicrobial, anticancer, anti-inflammatory
Flavonoids	Quercetin, kaempferol	Electron donation, stabilization	Antifungal, antibacterial, antioxidant
Phenolic acids	Gallic acid, chlorogenic acid	Metal-ion reduction	Free-radical scavenging
Terpenoids/steroids	β-sitosterol	Hydrophobic stabilization	Anti-inflammatory
Alkaloids	Nimbidin, nimbiol	Surface stabilization	Antimicrobial, antipyretic
Proteins/enzymes	Seed and gum proteins	Capping, colloidal stability	Improved biocompatibility
Polysaccharides	Gum carbohydrates	Growth control, dispersibility	Drug-delivery matrices
Vitamins	Ascorbic acid	Auxiliary reducing agent	Antioxidant

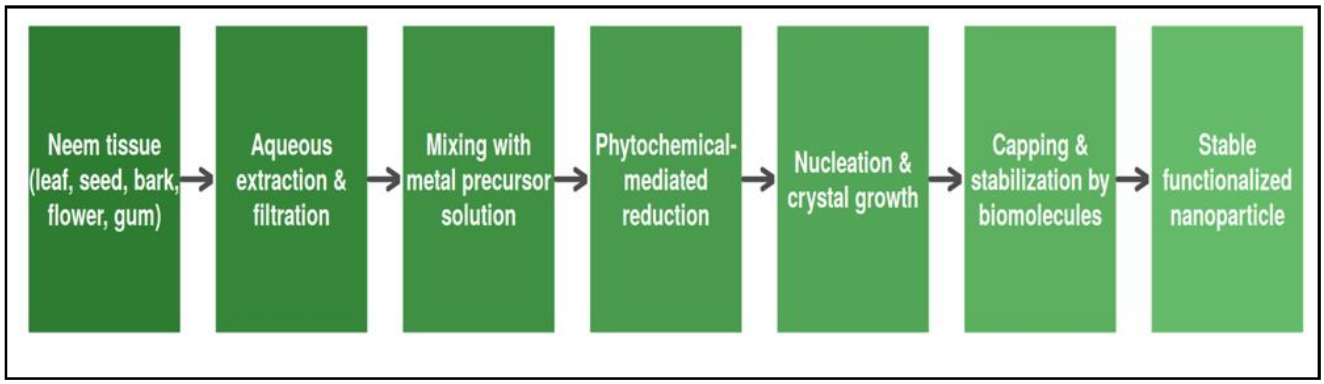


Figure 2: Schematic stages of *A. indica* mediated green nanoparticle synthesis, from tissue extraction through phytochemical mediated reduction, nucleation and capping to the stable functionalized product.

4. Fundamentals of phytonanotechnology

Phytonanotechnology integrates phytochemistry, nanoscience, biotechnology and green chemistry to synthesize nanomaterials using plant-derived biomolecules as reducing, stabilizing and, in some cases, shape-directing agents. Compared with physical methods (laser ablation, sputtering, evaporation condensation) and chemical methods (sodium borohydride or citrate reduction), plant mediated synthesis avoids toxic reagents, operates under mild aqueous conditions and produces nanoparticles with a bioactive phytochemical corona that improves biocompatibility.

The synthesis workflow generally proceeds through extraction of phytochemicals from the chosen *A. indica* tissue, mixing of the extract with a metal precursor solution, phytochemical-mediated reduction of metal ions, nucleation and crystal growth, and finally capping and stabilization of the resulting nanoparticles by adsorbed biomolecules. Reaction parameters such as extract concentration, precursor concentration, pH, temperature and reaction time strongly influence the size, shape, yield and crystallinity of the final product.

5. Mechanism of green nanoparticle synthesis using *A. indica*

The overall workflow, from tissue selection through to a stable, phytochemical-capped nanoparticle, proceeds through a consistent sequence of stages regardless of the target metal (Figure 2).

5.1 Preparation of plant extracts

A. indica leaves, seeds, bark, flowers, fruit pulp, fruit peel, gum and roots have all been used as source material for nanoparticle biosynthesis. Fresh or shade-dried tissue is washed, cut or pulverized and extracted in distilled water (or occasionally ethanol) under mild heating, then filtered to obtain a phytochemical rich extract that is combined with the metal precursor. Leaf extracts remain the most widely used source because of their high concentration of flavonoids, limonoids and phenolics, while seed and gum extracts contribute additional proteins and fatty constituents that improve nanoparticle stability.

5.2 Phytochemical mediated reduction, nucleation and stabilization

Once the *A. indica* extract is combined with a metal salt solution (for example silver nitrate, chloroauric acid, zinc acetate, copper acetate or ferric/ferrous salts), hydroxyl and carbonyl bearing limonoids and flavonoids donate electrons that reduce dissolved metal ions to their zero valent or oxide form. Formation of nanoparticles is typically signalled by a visible colour change (for example, pale yellow to reddish-brown for silver, or ruby-red for gold) and confirmed by a characteristic surface plasmon resonance band on UV-Visible spectroscopy. Continued adsorption of proteins, polysaccharides and phenolics onto the nascent nanoparticle surface arrests further growth and provides electrostatic and steric stabilization against aggregation, as evidenced by negative zeta potential values commonly reported in *A. indica* mediated syntheses.

5.3 Factors influencing synthesis

The pH of the reaction mixture affects the ionization state of phenolic and carboxyl groups and therefore the rate of electron transfer; mildly alkaline conditions generally favour smaller, more uniform nanoparticles. Temperature accelerates reaction kinetics and nucleation, with moderate heating typically producing smaller particles than prolonged synthesis at ambient temperature. The extract to precursor ratio and reaction time further determines particle size, polydispersity and yield, requiring empirical optimization for each combination of *A. indica* tissue and metal precursor.

6. Types of nanoparticles synthesized using *A. indica*

A. indica extracts have been used to fabricate a wide range of metallic and metal oxide nanoparticles, most commonly silver, gold, zinc oxide and copper oxide, with a growing body of work on iron oxide, magnesium oxide and other metal oxide nanoparticles (Table 2 and Figure 3).

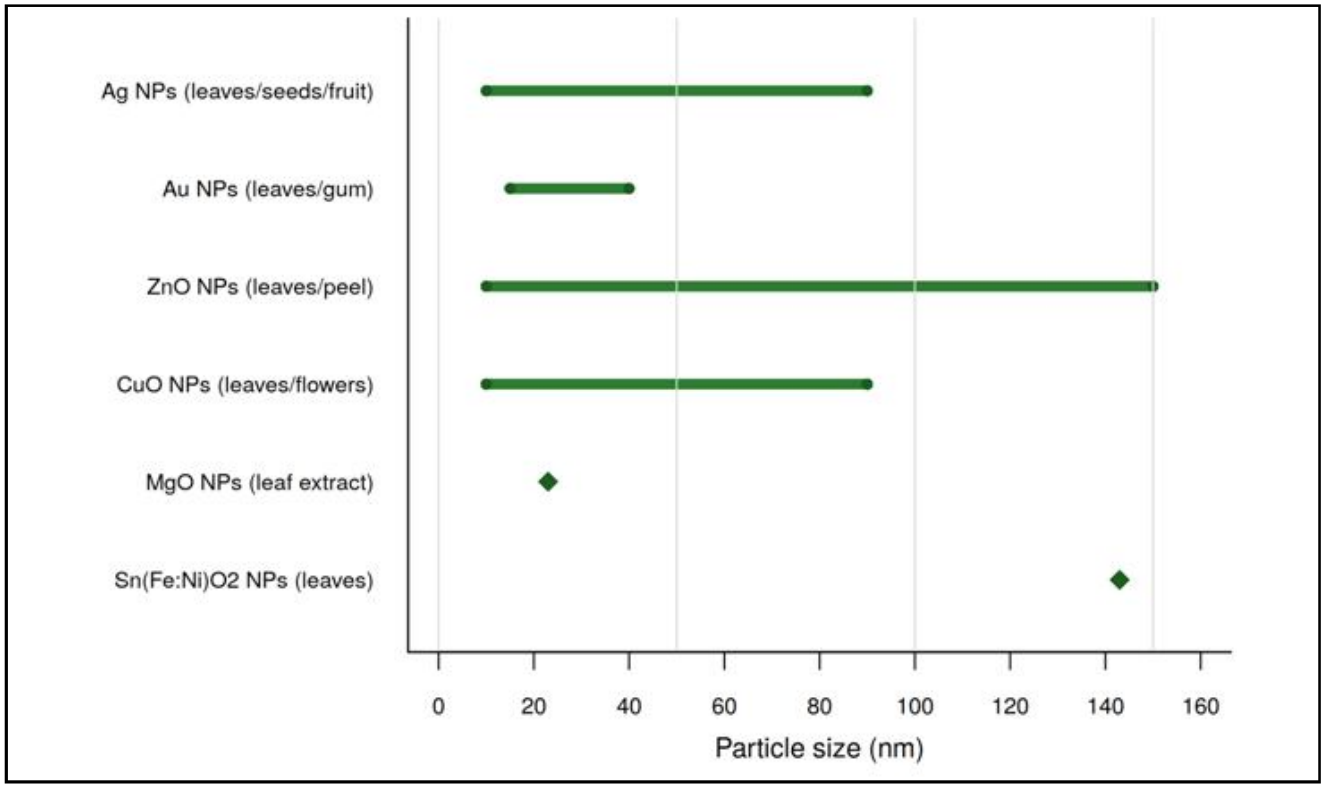


Figure 3: Reported particle-size ranges of A. indica mediated nanoparticles

6.1 Silver nanoparticles (AgNPs)

Silver nanoparticles are the most extensively reported *A. indica* derived nanomaterial. Asimuddin *et al.* (2020) reduced Ag^{+} ions from silver nitrate using *A. indica* leaf extract into spherical AgNPs with a UV-Visible absorption maximum near 455 nm and confirmed antibacterial and cytotoxic effects, while Deka *et al.* (2021) similarly obtained antioxidant, antibacterial leaf-mediated AgNPs. Qualitative phytochemical screening of the leaf extracts used in these syntheses has confirmed the presence of steroids, alkaloids, phenolics, tannins, flavonoids, saponins and terpenoids. Rehman *et al.* (2023) used *A. indica* seed extract to synthesize AgNPs evaluated for antidiabetic potential through glucose-uptake, glucose-adsorption and alpha-amylase inhibition assays, reporting measurable reductions in blood glucose in streptozotocin-induced diabetic mice. Alampally *et al.* (2025) produced *A. indica* fruit-pulp AgNPs (30-40 nm, zeta potential -36.7 mV) with demonstrated antioxidant, antibacterial and anticancer activity against a breast cancer cell line, and Alharbi and Alsubhi (2022) reported comparable anticancer efficacy for AgNPs synthesized from *A. indica* fruit extract. Aljazzar *et al.* (2026) used mixed leaf-and-root extracts to obtain AgNPs with strong colorimetric heavy-metal sensing capability toward Hg^{2+}, Pb^{2+} and Cd^{2+} alongside antibacterial action, and Barik *et al.* (2024) synthesized leaf-mediated AgNPs (86 nm, -26.9 mV) for periodontal treatment, reporting strong antibiofilm and antioxidant activity together with molecular docking evidence implicating quercetin in bacterial biofilm protein binding. Lakkim *et al.* (2020) additionally showed that *A. indica* derived AgNPs inhibit multidrug resistant Klebsiella pneumoniae and accelerate wound closure in a murine model. The SPR peaks reported across several of these independent studies are compared in Figure 4, and the corresponding particle size ranges are summarized alongside other *A. indica* derived nanomaterials in Figure 3.

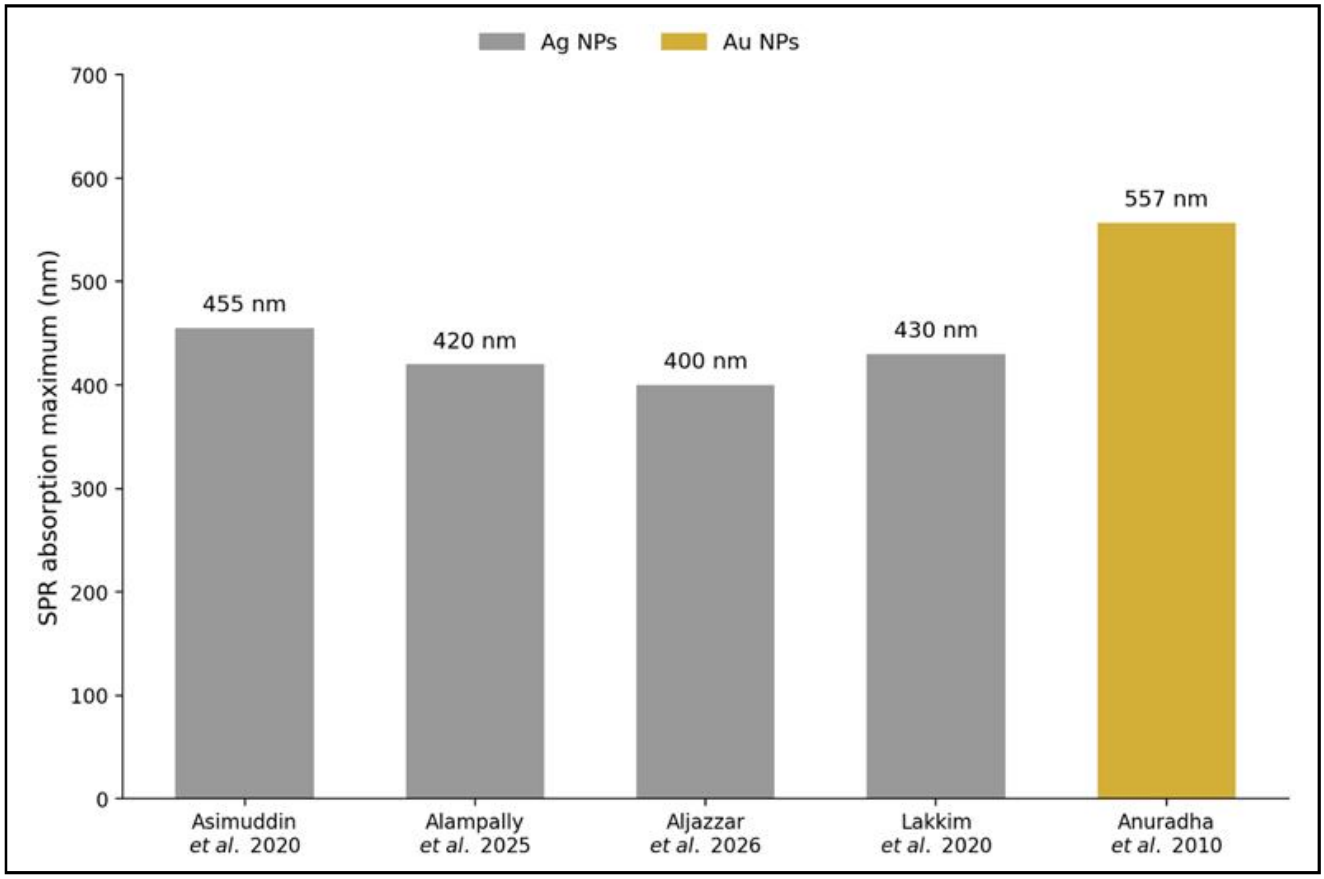


Figure 4: Surface plasmon resonance (SPR) absorption maxima reported for *A. indica* mediated silver and gold nanoparticles across independent studies.

6.2 Gold nanoparticles (AuNPs)

Anuradha *et al.* (2010) demonstrated that *A. indica* aqueous extract reduces chloroauric acid ($HAuCl_4$) into gold nanoparticles through a rapid, room temperature, biomimetic reaction, with the characteristic plasmon absorption band stabilizing near 557 nm and consistent with fairly uniform, quasi-spherical particles. *A. indica* gum coated gold nanoparticles have further been explored in the review by Kumari *et al.* (2025) as nanocarriers capable of ferrying the antipsychotic drug haloperidol across the blood brain barrier, illustrating the potential of *A. indica* derived AuNPs in central nervous system drug delivery.

6.3 Zinc oxide nanoparticles (ZnO NPs)

ZnO NPs represent one of the best-characterized classes of *A. indica* mediated metal oxide nanoparticles. Bhuyan *et al.* (2015) synthesized spherical, wurtzite-structured leaf-mediated ZnO NPs with a band gap near 3.87 eV, showing good antibacterial activity against *S. aureus, S. pyogenes* and *E. coli* together with photocatalytic dye degradation.

Sakthivel and Mallika (2016) similarly obtained ZnO NPs from *A. indica* gum exudate with confirmed antifungal activity, while Halder *et al.* (2025) showed that *A. indica* leaf extract functionalizes and enhances the antibacterial activity of ZnO NPs, particularly against the Gram-positive *B. subtilis*. Ahmed *et al.* (2022) demonstrated that *A. indica* mediated ZnO NPs control *A. niger* induced fruit rot in litchi, underscoring their agricultural relevance alongside biomedical potential, and the review by Patil *et al.* (2022) catalogues a wider set of *A. indica* leaf derived metal oxide nanoparticles, including ZnO, evaluated for antibacterial, anticancer and photocatalytic applications.

6.4 Copper and copper oxide nanoparticles (CuNPs/CuO NPs)

Copper oxide nanoparticles offer a low-cost alternative to silver with comparable antimicrobial efficacy. Joshi *et al.* (2025) synthesized *A. indica* leaf-mediated CuO NPs that showed pronounced antifungal activity against *C. gloeosporioides* and extended the postharvest shelf life of mango fruit without raising copper residues above safety thresholds. Jayakodi *et al.* (2022) used *A. indica* flower extract to produce CuO NPs (10.11-17.54 nm) and evaluated their cytotoxicity in H9c2 cardiomyocyte cells alongside an ecotoxicity assessment in zebrafish (Danio rerio) embryos, while Kumar *et al.* (2024) and Tabassum *et al.* (2025) reported additional *A. indica* leaf-mediated CuO NPs with confirmed antibacterial and photocatalytic properties, the latter incorporating recovered electronic-waste cable material as a copper source.

6.5 Iron oxide and other metal oxide nanoparticles

Akhtar *et al.* (2024) synthesized magnetite iron oxide nanoparticles using *A. indica* leaf extract, including composites loaded onto reduced graphene oxide, and demonstrated photocatalytic degradation of methylene blue dye, exploiting both the magnetic recoverability of the iron oxide core and the phytochemical coating derived from the *A. indica* extract to enhance colloidal stability and catalytic performance. Sharma *et al.* (2016) used *A. indica* leaf extract to obtain tetragonal hausmannite Mn_3O_4 nanoparticles with notable thermal catalytic and chemical sensing performance, and Aloufi (2023) synthesized *A. indica* leaf mediated tin-iron-nickel oxide, Sn (Fe:Ni)O_2, nanoparticles (hydrodynamic diameter 143 nm) with confirmed antibacterial activity against several Gram-positive and Gram-negative pathogens.

6.6 Magnesium oxide nanoparticles (MgO NPs)

Al-Harbi *et al.* (2024) reported bioinspired MgO nanoparticles synthesized from *A. indica* extract as spherical particles with an average size near 23 nm, exhibiting good thermal and biological-media stability. These MgO NPs displayed notable free-radical scavenging activity together with antibacterial, antidiabetic and anti-inflammatory effects, outperforming both the crude extract and chemically synthesized MgO controls in several assays.

6.7 Comparative overview

Taken together, the studies summarized in Table 2 and Figure 3 show that *A. indica* mediated nanoparticle size is strongly influenced by both the metal precursor and the plant tissue used, with silver, copper oxide and zinc oxide nanoparticles spanning the broadest reported ranges and magnesium oxide and Sn (Fe:Ni)O_2 nanoparticles being reported at more tightly defined sizes in single studies.

Table 2: *A. indica* mediated metallic and metal oxide nanoparticles: Plant sources, size ranges, and principal biological activities

Nanoparticle	Plant part commonly used	Typical size range (nm)	Principal reported activities
Silver (AgNPs)	Leaves, seeds, fruit pulp, roots	10-90	Antibacterial, anti-diabetic, anticancer, antibiofilm, heavy-metal sensing
Gold (AuNPs)	Leaves, gum	15-40	Drug delivery (blood-brain-barrier transport), biocompatible carriers
Zinc oxide (ZnO)	Leaves, fruit peel	10-150	Antibacterial, photocatalytic, antifungal biocontrol, supercapacitor
Copper/CuO	Leaves, flowers	10-90	Antifungal, antibacterial, postharvest preservation, cytotoxicity screening
Iron oxide (Fe3O4)	Leaves	~11	Photocatalytic dye degradation, magnetic recoverability
Magnesium oxide (MgO)	Leaves/extract	~23	Antioxidant, antibacterial, antidiabetic, anti-inflammatory
Selenium/Fe-Se	Leaves	nanoflower morphology	Anticancer (breast cancer cell lines), apoptosis induction

7. Pharmacological uses and biomedical applications of *A. indica* mediated nanoparticles

The phytochemical corona surrounding *A. indica* derived nanoparticles, dominated by limonoids, flavonoids and proteins, confers antimicrobial, antioxidant, anti-inflammatory and anticancer functionality that extends beyond the intrinsic activity of the metal or metal oxide core. This synergy has driven exploration of *A. indica* mediated nanoparticles across several biomedical and agricultural domains.

7.1 Drug delivery systems

Gold and gum-coated *A. indica* nanoparticles have been reviewed by Kumari *et al.* (2025) as nanocarriers capable of transporting therapeutic molecules such as haloperidol across the blood-brain barrier, illustrating the suitability of *A. indica* derived nanocarriers for central nervous system targeted delivery. Phytochemically stabilized nanoparticles more broadly improve drug loading, colloidal stability and circulation time, supporting both passive tumour accumulation *via* the enhanced permeability and retention effect and active, ligand mediated targeting.

7.2 Cancer therapy

Alampally *et al*. (2025) reported that *A. indica* fruit-pulp AgNPs show notable anticancer activity against breast cancer cells alongside antioxidant and antibacterial effects, and Alharbi and Alsubhi (2022) similarly demonstrated anticancer activity for *A. indica* fruit-derived AgNPs. Jayakodi *et al*. (2022) evaluated the cytotoxic profile of *A. indica* flower CuO NPs in cardiomyocyte cells as part of a broader ecotoxicity assessment relevant to nanomedicine safety screening. These findings support the potential of *A. indica* mediated nanoparticles as adjuncts to conventional chemotherapy, potentially reducing effective drug doses and associated systemic toxicity.

7.3 Antimicrobial coatings and antibiofilm applications

A. indica derived AgNPs, ZnO NPs and CuO NPs consistently demonstrate broad-spectrum activity against Gram-positive and Gram-negative bacteria and, in several studies, against fungal pathogens (Bhuyan *et al*., 2015; Asimuddin *et al*., 2020; Halder *et al*., 2025). Barik *et al*. (2024) showed strong antibiofilm and antioxidant action for *A. indica* leaf AgNPs relevant to periodontal disease management, while Aloufi (2023) and Tabassum *et al*. (2025) investigated *A. indica* mediated metal oxide nanoparticles for surface coating and photocatalytic applications aimed at limiting microbial colonization.

7.4 Wound healing

Lakkim *et al*. (2020) combined *A. indica* extract with *C. roseus* extract to synthesize AgNPs evaluated against multidrug-resistant bacteria isolated from septic wounds, reporting a 16 mm zone of inhibition against *K. pneumoniae* and 87% wound-healing efficacy in a murine model, supporting the use of *A. indica* mediated AgNPs in infected wound management.

7.5 Tissue engineering and regenerative applications

Although direct scaffold work with *A. indica* derived nanoparticles remains limited relative to Moringa or Aloe-based systems, the antioxidant and anti-inflammatory properties documented for *A. indica* mediated MgO and AgNPs suggest potential for incorporation into wound dressings, hydrogels and composite scaffolds intended to modulate the local oxidative and inflammatory environment during tissue repair.

7.6 Diagnostic and sensing applications

Aljazzar *et al*. (2026) showed that *A. indica* mediated AgNPs synthesized from mixed leaf-and-root extracts exhibit strong colorimetric sensing capability for heavy metals, producing visible and spectral colour changes on exposure to Hg^{2+}, Pb^{2+} and Cd^{2+} ions. This dual antimicrobial-sensing functionality highlights the potential of *A. indica* derived nanomaterials for low cost point of need environmental and diagnostic sensing platforms.

7.7 Antidiabetic and metabolic applications

Rehman *et al*. (2023) showed that AgNPs synthesized from *A. indica* seed extract exhibit measurable *in vitro* glucose adsorption, yeast cell glucose uptake and alpha amylase inhibitory activity, together with reduced blood glucose levels in streptozotocin induced diabetic mice, while Al-Harbi *et al*. (2024) demonstrated comparable antidiabetic activity for bioinspired *A. indica* mediated MgO nanoparticles alongside antioxidant and anti-inflammatory effects, positioning *A. indica* mediated nanoparticles as candidates for adjunctive metabolic disease management.

7.8 Agricultural and postharvest applications

Because *A. indica* itself is a long-established botanical pesticide, *A. indica* mediated nanoparticles have found particularly strong traction in agriculture. Ahmed *et al*. (2022) showed that *A. indica* mediated ZnO NPs control *A. niger* induced fruit rot in litchi, while Joshi *et al*. (2025) demonstrated that *A. indica* mediated CuO NPs suppress anthracnose in mango and extend postharvest shelf life without raising copper residues above safety thresholds, illustrating a translational pathway from green nanosynthesis to field relevant crop protection.

7.9 Dental and periodontal applications

Given *A. indica*'s traditional use in oral hygiene (as chewing sticks and in toothpaste formulations), Barik *et al*. (2024) specifically evaluated *A. indica* mediated AgNPs for periodontal treatment, reporting spherical, nanosized (about 86 nm), negatively charged particles with strong antibacterial and antioxidant action against biofilm forming periodontal pathogens, supporting further development of *A. indica* nanoparticle based oral care formulations.

7.10 Environmental remediation

Akhtar *et al*. (2024) and Aloufi (2023) demonstrated that *A. indica* mediated iron oxide and Sn (Fe:Ni)O_2 nanoparticles, respectively, degrade or help remove organic pollutants such as methylene blue, while Tabassum *et al*. (2025) showed photocatalytic activity for *A. indica* mediated CuO nanoparticles under solar or UV irradiation, indicating a secondary but valuable role for these nanomaterials in wastewater treatment and environmental clean-up.

8. Future prospects

Future work should prioritize standardization of extraction and synthesis protocols across *A. indica* plant parts to improve reproducibility, together with systematic optimization of pH, temperature, precursor concentration and extract ratio for each metal *A. indica* tissue combination. Multi-omics approaches (metabolomics, proteomics) could help identify the specific limonoid and flavonoid fractions most responsible for efficient reduction and stabilization, enabling rational, targeted extract formulation rather than empirical whole-extract use. Integration of artificial intelligence and machine learning may accelerate parameter optimization and property prediction, while comprehensive *in vivo* toxicity, pharmacokinetic and biodistribution studies remain essential before *A. indica* mediated nanomaterials can progress toward clinical or large-scale agricultural deployment. Given *A. indica*'s dual reputation as both a medicinal and pesticidal plant, continued cross disciplinary collaboration between pharmacologists, agronomists, nanotechnologists and regulatory bodies will be important for realizing its full translational potential.

9. Conclusion

Azadirachta indica is a chemically rich, widely available and economically accessible biological resource for the green synthesis of a broad range of metallic and metal oxide nanoparticles. Its limonoid and flavonoid dominated phytochemistry enables efficient reduction, capping and stabilization of silver, gold, zinc oxide, copper oxide, iron oxide, magnesium oxide and selenium nanoparticles, many of which display antimicrobial, antidiabetic, anticancer, antioxidant and photocatalytic activities that exceed those of the corresponding chemically synthesized materials. *A. indica* mediated nanoparticles

have already shown translational promise in wound care, periodontal treatment, postharvest crop protection, environmental remediation and early-stage drug delivery and cancer-therapy research. Continued interdisciplinary work on synthesis standardization, mechanistic characterization and biosafety evaluation will be necessary to move these promising laboratory findings toward reliable clinical, agricultural and industrial application.

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Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

H. B. Roghan: Conceptualization, academic oversight, critical review and validation of scientific content; **V. Kabinesh**: Software handling and data curation.

Consent for publication

All authors gave full consent for publication and submission to this journal.

Ethical approval

Not applicable.

Conflict of interest

The authors declare no conflict of interest relevant to this article.

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