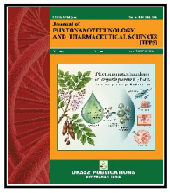
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Phytonanotechnology of *Pongamia pinnata* (L.) Pierre: Green synthesis, characterization and multifunctional biomedical applications

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Abstract

Phytonanotechnology represents an emerging interdisciplinary approach integrating green chemistry, nanotechnology and plant biotechnology for the sustainable synthesis of functional nanomaterials. *Pongamia pinnata* (L.) Pierre, commonly known as Pungam or Karanja, has gained increasing attention as a promising plant source for nanoparticle biosynthesis due to its diverse phytochemical profile. Its leaves, seeds, bark, flowers and seed oil contain bioactive constituents, particularly the characteristic furanoflavonoids karanjin and pongamol, along with pongapin, kanjone, glabrin, flavonoids, phenolic compounds, tannins, alkaloids, terpenoids, steroids, proteins and polysaccharides. These metabolites contribute to the reduction, stabilization and capping of nanoparticles during green synthesis. This review critically summarizes recent advances in *P. pinnata* mediated synthesis of metallic and metal oxide nanoparticles, including silver, gold, zinc oxide, copper oxide, iron oxide, selenium, titanium dioxide, cadmium sulfide, copper nanoferrite and trimetallic Ag-Cu-TiO_2 nanoparticles. Particular emphasis is placed on phytochemical-mediated reduction mechanisms, nucleation, crystal growth, stabilization and the influence of synthesis parameters on nanoparticle properties. Major characterization approaches, including UV-Visible spectroscopy, FTIR, XRD, SEM, TEM, DLS, zeta potential, EDX and GC-MS, are also discussed. The biomedical applications of these nanomaterials in antimicrobial therapy, drug delivery, cancer treatment, wound healing, tissue engineering, diagnostic imaging, antidiabetic, dermatological, dental and ophthalmic applications are reviewed. Key challenges include reproducibility, standardization, scalability, biosafety and regulatory validation. Future integration of artificial intelligence, omics and precision nanomedicine may facilitate the development of safer and more effective *P. pinnata* derived nanoplatforms.

1. Introduction

Nanotechnology has emerged as one of the most transformative scientific disciplines of the twenty-first century, offering unprecedented opportunities for innovation in medicine, agriculture, environmental remediation, food technology and energy systems. Nanoparticles, typically ranging from 1 to 100 nm in size, possess unique physicochemical properties including high surface area-to-volume ratio, enhanced catalytic activity, tuneable optical characteristics and improved biological interactions that distinguish them from their bulk counterparts. These distinctive properties have facilitated the development of advanced drug delivery systems, biosensors, antimicrobial agents, diagnostic tools, tissue engineering scaffolds and multifunctional therapeutic platforms. However, conventional nanoparticle synthesis methods, which primarily rely on physical and chemical approaches, often require high energy consumption, expensive instrumentation, toxic reducing agents such as sodium borohydride and hydrazine hydrate, and hazardous solvents that pose significant environmental and health risks (Iravani, 2011; Mittal *et al*., 2013; Baig *et al*., 2021). Consequently, there has been a paradigm shift toward environmentally benign and biologically sustainable alternatives, giving rise to the rapidly evolving field of green nanotechnology.

Green nanotechnology integrates the principles of green chemistry and sustainable engineering with nanoscience to develop eco-friendly processes for nanoparticle synthesis while minimizing environmental impact throughout the production lifecycle. Unlike traditional methods, green synthesis employs naturally occurring biomolecules from microorganisms, algae, fungi and higher plants as reducing, capping and stabilizing agents (Narayanan and Sakthivel, 2010; Singh *et al*., 2016). Among these biological resources, plants have gained exceptional attention because they are readily available, inexpensive, renewable, biodegradable and rich in diverse phytochemicals capable of mediating nanoparticle formation under mild reaction conditions. Plant-mediated synthesis also eliminates the need for aseptic culture conditions required in microbial synthesis, making it highly suitable for large-scale industrial production. Moreover, green-synthesized nanoparticles often exhibit superior biocompatibility and enhanced biological activities due to the presence of phytochemical coatings on their surfaces, which improve stability, cellular interactions and therapeutic efficacy (Ahmed *et al*., 2016; Vanga and Satla, 2025).

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Among the numerous medicinal plants investigated for nanoparticle biosynthesis, *P. pinnata* has emerged as a particularly compelling but comparatively underexploited biological resource. Known regionally as Pungam (Tamil, Siddha), Karanja (Sanskrit, Ayurveda, Hindi), Honge (Kannada), Pongam or Indian beech (English) and traded as Poonga, the species belongs to the family Fabaceae and is extensively cultivated throughout tropical and subtropical Asia, Australia and the Pacific. The plant is highly valued for its rapid growth, nitrogen-fixing symbiosis with rhizobia, drought and salinity tolerance, adaptability to marginal and degraded soils and year-round availability, making it an economically viable and ecologically restorative resource for sustainable nanotechnology (Kesari *et al*., 2010; Biswas *et al*., 2011; Sreeharsha *et al*., 2016). Critically, *P. pinnata* is a non-edible oilseed tree; harvesting its leaves, bark, pods and seeds for nanomaterial production therefore creates no competition with food supply, an advantage not shared by many food-crop-derived nanofactories.

Almost every part of the plant, including leaves, seeds, bark, flowers, roots, pods and seed oil, is utilized in traditional Ayurvedic, Siddha and Unani medicine for bronchitis, whooping cough, rheumatic joint pain, diabetes, skin disorders, ulcers and wound management (Pulipati *et al*., 2018; Al Muqarrabun *et al*., 2013). These plant parts contain abundant bioactive compounds, most distinctively the furanoflavonoids karanjin and pongamol together with pongapin, kanjone, kanugin, demethoxykanugin, glabrin and the pongamol series, alongside flavones, flavans, chalcones, phenolic acids, tannins, alkaloids, triterpenes, steroids (β-sitosterol, stigmasterol), proteins, polysaccharides and fatty acids dominated by oleic acid. These phytochemicals function synergistically as natural reducing, capping and stabilizing agents during nanoparticle synthesis, enabling efficient conversion of metal ions into stable nanostructures without hazardous chemicals (Pavithra *et al*., 2016; Cui *et al*., 2025).

The convergence of phytochemistry and nanotechnology has led to the emergence of phytonanotechnology, an interdisciplinary field that explores the use of plant-derived biomolecules for the eco-friendly synthesis, functionalization and biomedical application of nanomaterials. Despite the rapid growth of research on *P. pinnata*-mediated nanoparticle synthesis, current knowledge remains fragmented across diverse scientific disciplines, with limited comprehensive reviews integrating phytochemistry, synthesis mechanisms, physicochemical characterization, biological functions, biomedical applications, toxicity assessment, regulatory considerations and future translational opportunities. Accordingly, this review aims to provide a comprehensive overview of the phytochemical basis of Pungam-mediated green nanoparticle synthesis, elucidate the underlying mechanisms, summarize the major characterization techniques, critically evaluate recent advances in antimicrobial, antioxidant, anticancer, anti-inflammatory, wound healing and drug delivery applications, and discuss biosafety, toxicity, regulatory challenges and emerging future trends.

2. Botanical overview of *P. pinnata*

P. pinnata is a medium-sized, glabrous, semi-evergreen to semi-deciduous tree growing to 15-20 m in height with a short bole, spreading crown and greyish-green to brown bark. Taxonomically it is classified under Kingdom Plantae, Division Magnoliophyta (Angiosperms), Class Magnoliopsida (Dicotyledons), Order Fabales, Family Fabaceae (subfamily Papilionoideae), Genus *Pongamia* and Species *P. pinnata*. The species carries several accepted synonyms, notably *Millettia pinnata* (L.) Panigrahi, *Derris indica* (Lam.) Bennet, *Pongamia glabra* Vent. and *Cytisus pinnatus* L., a nomenclatural multiplicity that complicates literature retrieval and must be borne in mind when surveying nanotechnology reports, since studies are indexed under both *Pongamia* and *Millettia* (Al Muqarrabun *et al*., 2013; Sreeharsha *et al*., 2016).

The species is native to the sub-Himalayan tracts and coastal regions of India, Southeast Asia, northern Australia and Indonesia, and has been introduced widely across tropical Africa, the Pacific islands and the Americas. Leaves are imparipinnate with five to nine ovate, glossy leaflets; flowers are pinkish-white to lavender papilionaceous racemes; and fruits are flattened, indehiscent, woody pods containing one or two reniform seeds. Seed oil content ranges from 30 to 50% of dry weight, of which roughly 55% is oleic acid, making the species a leading non-edible biodiesel feedstock (Sreeharsha *et al*., 2016; Kazakoff *et al*., 2012). Its dense lateral root network binds sand dunes and controls erosion, its long taproot confers drought tolerance and mature trees withstand waterlogging, mild frost and high salinity. The nitrogen-fixing capability, conferred by root nodulation with rhizobia, permits cultivation on degraded land with minimal fertilizer input (Biswas *et al*., 2011; Kesari *et al*., 2010). Collectively these traits make Pungam biomass an abundant, low-cost, regenerating and ethically uncontested feedstock for phytonanotechnology.

3. Phytochemical profile of *P. pinnata*

The remarkable ability of *P. pinnata* to mediate green nanoparticle synthesis is largely attributed to its distinctive phytochemical composition. Plant extracts contain numerous secondary metabolites and biomacromolecules capable of reducing metal ions into nanoparticles while simultaneously acting as stabilizing and capping agents. These phytochemicals not only determine nanoparticle size, morphology, crystallinity and stability but also enhance biological activities by forming bioactive surface coatings (Table 1). Preliminary phytochemical screening of leaf, bark and seed extracts consistently reveals alkaloids, steroids, carbohydrates, tannins, flavonoids, terpenoids, coumarins, phenols, quinones, saponins and glycosides (Singh *et al*., 2016b; Pulipati *et al*., 2018).

3.1 Furanoflavonoids: Karanjin and pongamol

The chemotaxonomic signature of *P. pinnata* is its family of furanoflavonoids, a class scarcely represented in other nanoparticle-synthesizing plants. Karanjinis the principal furanoflavonoid, reported at concentrations as high as 349 ± 2.16 mg g^{-1} in methanolic seed extracts (Paul and Londhe, 2019). Karanjin exhibits documented antidiabetic, anticancer, antioxidant, gastroprotective, anti-inflammatory, antibacterial and anti-Alzheimer activities, and its drug-likeness and ADMET profile have been validated computationally (Noor *et al*., 2020; Ryan *et al*., 2024). During nanoparticle synthesis the methoxy and carbonyl substituents of the chromenone nucleus coordinate metal ions, while the conjugated furan-fused ring system supports electron delocalization favourable to reduction.

Pongamol, a β-diketone-type flavonoid existing in keto-enol tautomeric equilibrium, is arguably the most mechanistically informative constituent. Its structure contains one hydroxyl and one carbonyl group in the enol form, enabling it to act simultaneously as a reducing agent and as a capping ligand with high affinity for metal ions. Cui *et al*. (2025) purified pongamol by two-solvent

recrystallization at pH 5.8 and demonstrated one-pot, room-temperature synthesis of colloidally stable iron nanoparticles using pongamol alone, providing direct single-molecule proof of the dual reducing-capping role that is usually inferred only indirectly from crude extracts. Related furanoflavonoids, including pongapin, kanjone, kanugin, demethoxykanugin, glabrin and pongaglabrone, contribute additional chelation sites (Figure 1).

3.2 Flavonoids and phenolic acids

Beyond the furanoflavonoid series, *P. pinnata* contains flavones, flavans, chalcones, quercetin and kaempferol derivatives, catechins and condensed tannins. Their multiple hydroxyl groups readily donate electrons to metal ions, promoting nucleation and nanoparticle formation while preventing aggregation through surface adsorption. Phenolic acids including gallic, chlorogenic, caffeic, ferulic and p-coumaric acids participate actively in nucleation through electron donation and stabilize synthesized nanoparticles by surface adsorption. Their antioxidant activity contributes directly to the enhanced free-radical scavenging performance of the resulting nanomaterials (Rajeshkumar, 2016; Shahzadi *et al*., 2025).

3.3 Proteins, peptides and coagulant biomolecules

Leaf and seed proteins, enzymes and antimicrobial peptides serve as efficient capping agents. Functional groups such as amino, carboxyl and sulfhydryl residues bind strongly to nanoparticle surfaces, preventing aggregation and increasing colloidal stability. Spectroscopic evidence is unusually direct for this species: Paul and Londhe (2019) and Telange *et al*. (2024) identified interactions between silver and the O–H, C=O and amide I carbonyl groups of seed protein extract, while Beg *et al*. (2017) characterized the binding of seed-derived silver nanoparticles to human serum albumin, demonstrating that the protein corona formed during synthesis governs subsequent biological interfacing.

3.4 Terpenoids, steroids and alkaloids

Terpenoids and phytosterols including β-sitosterol, stigmasterol and lupeol facilitate nanoparticle formation by acting as natural reducing molecules and hydrophobic stabilizers, and further contribute anti-inflammatory and anticancer properties. Alkaloids and other nitrogen-containing compounds contribute to nanoparticle stabilization through coordination with metal ions and surface adsorption. Glycosides, tannins, steroids and terpenoids were specifically identified by GC-MS as the bioactive substances facilitating trimetallic Ag-Cu-TiO_2 formation from leaf extract (Nithya *et al*., 2025).

3.5 Seed oil and fatty acids

Pungam seed oil, comprising 30-50% of seed dry weight and dominated by oleic acid (approximately 55%), together with palmitic, stearic and linoleic acids, contributes to nanoparticle stability through hydrophobic interactions at the nanoparticle interface and serves as a matrix for encapsulated controlled-release formulations. Polyurea-encapsulated Pungam seed oil formulations have demonstrated sustained-release insecticidal bioefficacy, illustrating the versatility of the oil fraction as a nanocarrier matrix in addition to its established biodiesel role (Kumar *et al*., 2021).

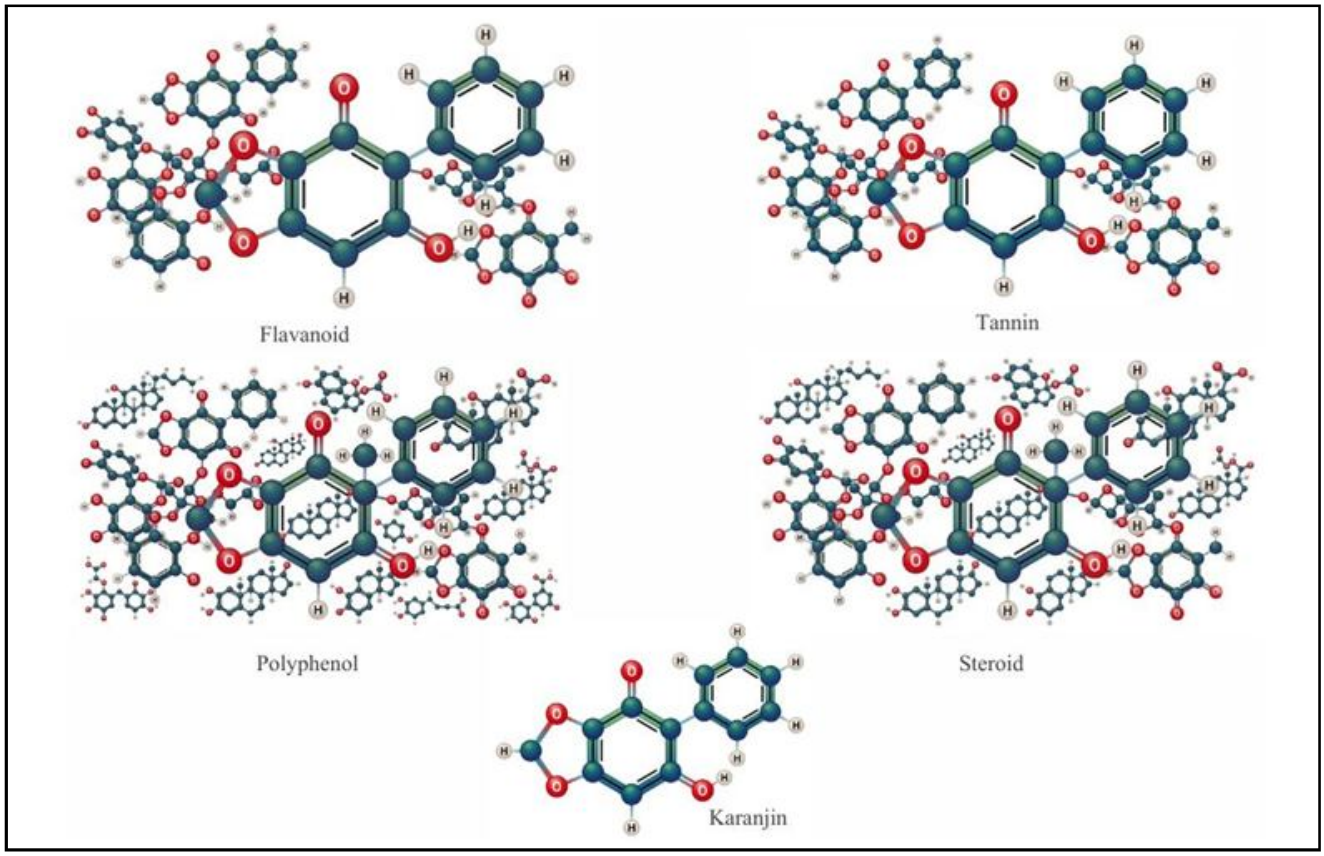


Figure 1: Chemical structure of pharmaceutical compounds seen in *P. pinnata*.

Table 1: Major phytochemicals of *P. pinnata* involved in green nanoparticle synthesis

Phytochemical class	Major compounds	Primary role in nanoparticle synthesis	Biomedical significance
Furanoflavonoids	Karanjin, pongamol, pongapin, kanjone	Dual reduction and capping; metal-ion chelation	Antidiabetic, anticancer, antioxidant
Flavonoids	Quercetin, kaempferol, flavones, chalcones	Electron donation and stabilization	Anti-inflammatory, antioxidant
Phenolic acids	Gallic, chlorogenic, caffeic, ferulic acids	Metal ion reduction and nucleation	Free radical scavenging
Tannins	Condensed and hydrolysable tannins	Reduction and surface adsorption	Antimicrobial, astringent
Alkaloids	Nitrogen-containing bases	Surface stabilization via coordination	Neuroprotective, antimicrobial
Terpenoids and steroids	β-Sitosterol, stigmasterol, lupeol	Capping and hydrophobic stabilization	Anti-inflammatory, anticancer
Proteins and peptides	Seed proteins, enzymes, amide I residues	Capping and colloidal stabilization	Enhanced biocompatibility
Polysaccharides	Cellulose, pectin, gums	Stabilization and controlled growth	Drug delivery, biocompatibility
Fatty acids	Oleic, palmitic, stearic, linoleic acids	Interfacial hydrophobic stabilization	Encapsulation matrix, sustained release

4. Fundamentals of phytonanotechnology

Phytonanotechnology is an emerging interdisciplinary branch of nanoscience that integrates phytochemistry, nanotechnology, biotechnology, materials science and green chemistry to synthesize functional nanomaterials using plant-derived biomolecules. Unlike conventional nanoparticle fabrication, which often relies on hazardous chemicals and energy-intensive processes, phytonanotechnology exploits naturally occurring phytochemicals as reducing, stabilizing and capping agents. Plant metabolites facilitate the conversion of metal ions into stable nanoparticles under environmentally benign conditions while functionalizing nanoparticle surfaces, thereby enhancing physicochemical stability, biocompatibility and biological activity (Vanga and Satla, 2025; Lakhani *et al*., 2025).

The development of phytonanotechnology has evolved through successive advances in nanoscience, green chemistry and plant biotechnology. During the initial stages of nanotechnology in the late twentieth century, nanoparticle synthesis depended predominantly on physical methods such as laser ablation, evaporation-condensation, ball milling, sputtering and pyrolysis. Although these techniques produced highly pure nanoparticles with controlled crystallinity, they required sophisticated instrumentation, elevated temperatures, vacuum systems and substantial energy inputs, limiting sustainability and commercial feasibility. The subsequent introduction of chemical synthesis enabled large-scale production through reducing agents such as sodium borohydride, hydrazine, citrate and ethylene glycol, providing excellent control over particle morphology but generating toxic residues that restricted biomedical applications (Baig *et al*., 2021; Ilavenil *et al*., 2025).

Within phytonanotechnology, plant extracts function simultaneously as reducing agents, stabilizers, capping molecules and sometimes shape-directing agents. This multifunctionality greatly simplifies nanoparticle production while reducing costs and environmental burdens. The synthesis process generally begins with extraction of phytochemicals from leaves, seeds, flowers, bark or roots using water or environmentally friendly solvents. Following addition of a metal precursor solution, phytochemicals containing hydroxyl, carbonyl, amino, sulfhydryl and carboxyl functional groups donate electrons that reduce metal ions into their elemental state. Once reduced atoms reach supersaturation, they aggregate into stable nuclei that subsequently grow into nanoparticles through crystal growth mechanisms. Simultaneously, surrounding phytochemicals adsorb onto nanoparticle surfaces, forming a protective phytochemical corona that improves colloidal stability and biological functionality (Gu *et al*., 2025; Rani *et al*., 2023).

5. Mechanism of green nanoparticle synthesis using *P. pinnata*

Green synthesis of nanoparticles using *P. pinnata* has emerged as a promising approach in phytonanotechnology owing to the plant's distinctive furanoflavonoid chemistry and its ability to act as a natural nanofactory. Nearly every part of the plant contains abundant polyphenols, furanoflavonoids, flavonoids, tannins, proteins, amino acids, carbohydrates and terpenoids that participate directly in nanoparticle formation. During synthesis, these biomolecules convert dissolved metal ions into zero-valent metallic nanoparticles through oxidation-reduction reactions while simultaneously stabilizing the newly formed nanostructures against aggregation (Raut *et al*., 2010; Rajeshkumar, 2016; Cui *et al*., 2025).

The biosynthesis process generally consists of three sequential stages: preparation of phytochemical-rich plant extracts; phytochemical-mediated reduction and nucleation of metal ions; and stabilization and capping of the synthesized nanoparticles. The efficiency of each stage depends on multiple physicochemical parameters, including the type of plant tissue used, extraction conditions, pH, temperature, precursor concentration, reaction time and storage conditions.

5.1 Preparation of plant extracts

Preparation of plant extracts is the initial and one of the most critical steps because the concentration, composition and stability of

phytochemicals directly influence nanoparticle formation. Plant materials are thoroughly washed with running tap water followed by distilled water to remove soil particles, microorganisms and pesticide residues. Cleaned materials are either shade-dried or processed immediately depending on the target phytochemicals, then chopped or pulverized to increase extraction surface area before extraction using distilled water or environmentally friendly solvents such as ethanol or methanol. Aqueous extraction remains the most widely adopted method because it preserves water-soluble phytochemicals, avoids solvent toxicity and complies with green chemistry principles; decoction extraction has been used successfully for Pungam leaf-mediated CuO synthesis (Tramta *et al*., 2024). Following extraction, the solution is filtered through Whatman filter paper or centrifuged before mixing with the metal precursor.

Leaves are the most extensively investigated organ, containing high concentrations of flavonoids, phenolic acids, tannins, reducing sugars, proteins, chlorophyll and organic acids. Notably, Raut *et al*. (2010) demonstrated that dried leaf biomass, rather than fresh leaf broth, efficiently reduces silver ions, with biomass dosage governing both conversion rate and size uniformity, a finding of practical importance because dried biomass can be stored and transported without loss of reducing capacity. Bark extracts of *P. pinnata* have yielded polydisperse silver nanoparticles of 5-55 nm with a surface plasmon resonance band at 420 nm (Rajeshkumar, 2016). Seeds contain proteins, peptides, fatty acids, phytosterols and the highest karanjin concentrations; seed proteins adsorb onto nanoparticle surfaces providing steric hindrance against aggregation (Paul and Londhe, 2019; Beg *et al*., 2017). Flower and root extracts remain comparatively underexplored and represent a clear research gap.

5.2 Phytochemical-mediated reduction

Conversion of dissolved metal ions into stable nanoparticles is a complex physicochemical process governed by the synergistic action of multiple phytochemicals. Unlike chemical synthesis, where reducing and stabilizing agents are added separately, plant extracts provide an integrated biochemical system capable of simultaneously reducing metal ions, initiating nucleation, directing crystal growth, stabilizing surfaces and forming a bioactive phytochemical corona.

Electron transfer is the fundamental process initiating nanoparticle biosynthesis. Furanoflavonoids, flavonoids and phenolics containing hydroxyl (-OH) and carbonyl (C=O) functional groups undergo oxidation, releasing electrons that reduce dissolved metal ions (Ag^{+}, Au^{3+}, Zn^{2+}, Cu^{2+}, Fe^{3+}, SeO_3^{2-}) into their corresponding zero-valent atoms according to the generalized reaction $M^{n+} + ne^{-} \rightarrow M^{0}$, where M^{n+} represents the dissolved metal ion and M^{0} the reduced metallic atom. During oxidation, these compounds are converted into quinone or semiquinone intermediates. In the specific case of pongamol, the keto-enol tautomerism permits the molecule to shuttle between electron-donating and chelating configurations, which explains its unusual efficiency as a standalone reductant (Cui *et al*., 2025). FTIR analyses of Pungam-mediated systems consistently demonstrate shifts in hydroxyl, amino and carbonyl absorption bands before and after synthesis, confirming the active involvement of these functional groups.

Freshly synthesized nanoparticles possess high surface energy and a strong tendency to aggregate. Natural stabilization is a major advantage of plant-mediated synthesis because *P. pinnata* extracts contain proteins, flavonoids, tannins, polysaccharides, amino acids and organic acids that spontaneously adsorb onto nanoparticle surfaces, providing both electrostatic and steric stabilization. Zeta potential measurements confirm this effect quantitatively; Pungam-mediated trimetallic Ag-Cu-TiO_2 nanoparticles recorded an average surface charge of –15.4 mV, indicating moderate colloidal stability (Nithya *et al*., 2025).

5.3 Factors affecting nanoparticle synthesis

Physicochemical characteristics of Pungam-mediated nanoparticles are strongly influenced by reaction conditions, and careful optimization is essential for reproducible size, morphology, crystallinity, surface charge and biological activity. The pH of the reaction medium is among the most influential factors because it regulates ionization of phytochemicals, redox potential and metal ion availability. Alkaline conditions enhance dissociation of hydroxyl groups, increasing electron donation and accelerating reduction; nanoparticles synthesized under mildly alkaline conditions are therefore often smaller and more uniformly distributed than those synthesized under acidic conditions, whereas extremely acidic or highly alkaline environments may denature proteins or degrade sensitive furanoflavonoids. Temperature directly influences reaction kinetics, diffusion rates and nucleation efficiency; moderate temperatures usually produce smaller nanoparticles because rapid nucleation creates numerous crystal nuclei, while excessive temperatures degrade thermolabile metabolites and promote aggregation. Calcination temperature exerts a separate and additional effect on metal oxides: Sundrarajan *et al*. (2015) reported that Pungam-derived ZnO attained crystallinity at 350°C. These interacting effects are summarized graphically in Figure 2, which presents a response-surface representation of conversion yield across the pH-temperature domain together with the corresponding size-pH relationship.

Formal statistical optimization remains rare in this literature but is demonstrably valuable. Telange *et al*. (2024) applied a Box-Behnken experimental design to Pungam seed-extract-mediated silver nanoparticle synthesis, obtaining an optimized formulation with entrapment efficiency of approximately 79.35% and spherical particles of about 116 nm. Wider adoption of such designed-experiment approaches, rather than one-factor-at-a-time screening, would substantially improve reproducibility across laboratories.

6. Types of nanoparticles synthesized using *P. pinnata*

The phytochemical diversity of *P. pinnata* has established this species as an efficient biological resource for green synthesis of metallic and metal oxide nanoparticles. Depending on the precursor salt and synthesis parameters, Pungam extracts have been successfully employed to synthesize silver, gold, zinc oxide, copper oxide, iron, selenium, titanium dioxide, cadmium sulfide, copper nanoferrite and trimetallic nanoparticles with diverse physicochemical properties and biomedical applications (Table 2). Compared with chemically synthesized nanomaterials, Pungam-mediated nanoparticles generally exhibit superior biocompatibility, lower cytotoxicity, enhanced antioxidant activity and improved antimicrobial efficacy owing to the bioactive phytochemical corona adsorbed onto their surfaces. The considerable spread of reported particle sizes across nanoparticle types and plant organs is summarized in Figure 3.

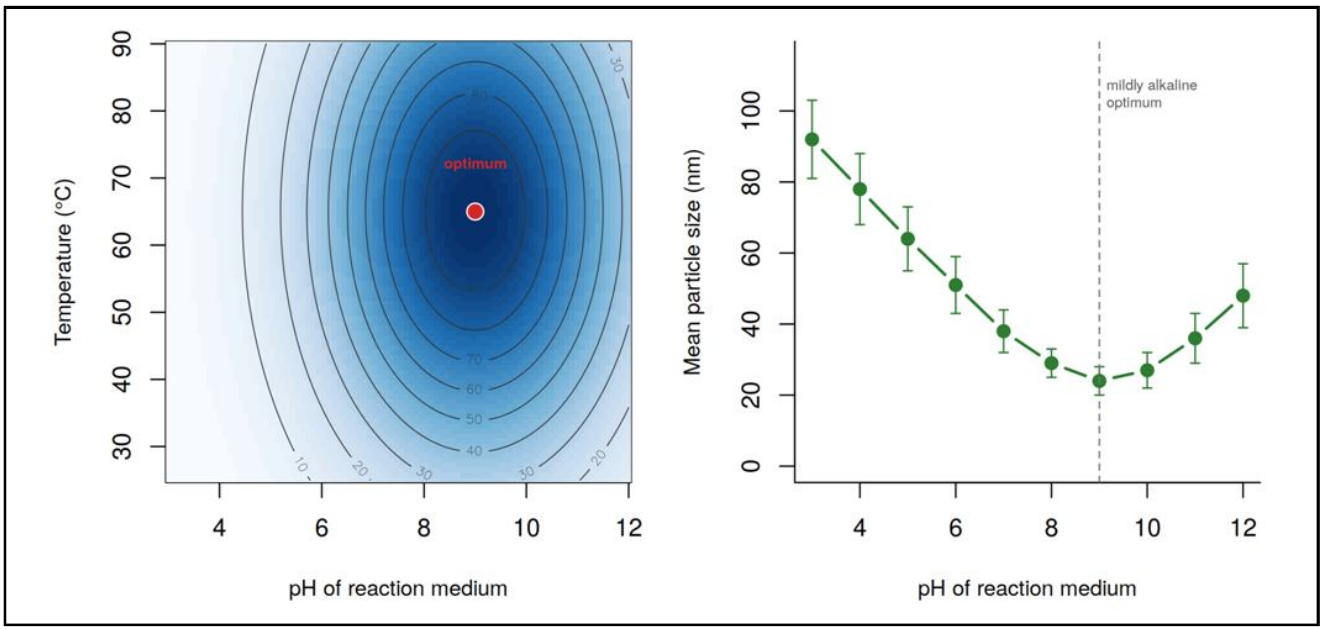


Figure 2: Influence of reaction parameters on *P. pinnata*-media-ted nanoparticle synthesis.

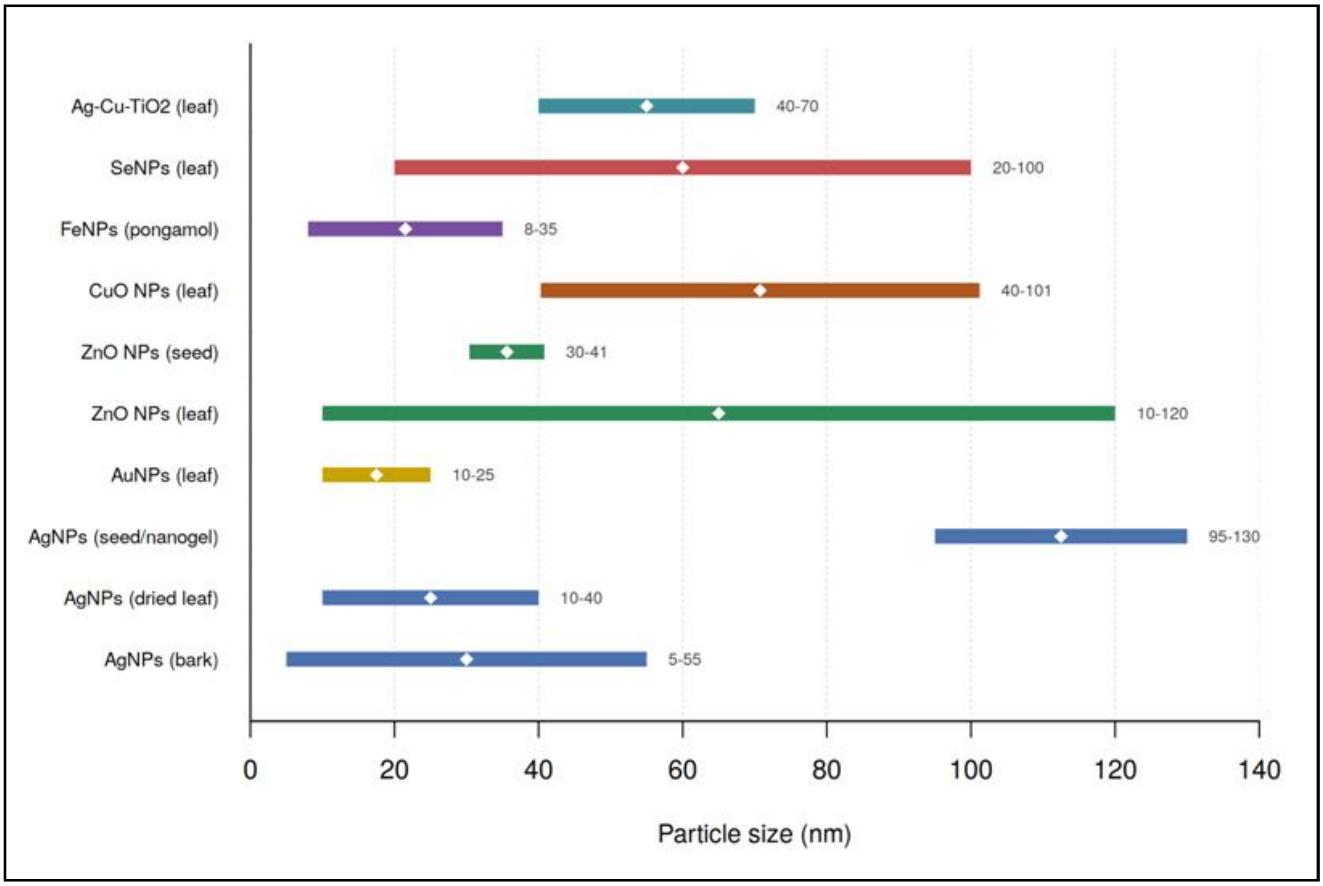


Figure 3: Reported particle-size ranges of *P. pinnata*-mediated nanoparticles.

6.1 Silver nanoparticles (AgNPs)

Silver nanoparticles are by a wide margin the most extensively investigated nanomaterials synthesized using *P. pinnata*, and the species has supported AgNP synthesis from at least four distinct organs. Raut *et al.* (2010) pioneered extracellular synthesis using dried leaf biomass, reporting XRD peaks at 2values of 38.06°, 44.64°,

64.58° and 77.62° corresponding to the (111), (200), (220) and (311) planes of face-centred cubic silver. Rajeshkumar (2016) employed fresh bark extract, obtaining a surface plasmon resonance band at 420 nm, polydisperse particles of 5-55 nm and a characteristic EDX signal at 3 keV confirming metallic silver. Paul and Londhe (2019) used methanolic seed extract with a karanjin content of 349 ± 2.16 mg g^{-1}, and Beg *et al*. (2017) characterized seed-derived AgNPs including their spectroscopic interaction with human serum albumin.

Biosynthesis of AgNPs is typically indicated by a colour change from pale yellow to dark brown due to surface plasmon resonance, with UV-Visible absorption peaks generally between 410 and 450 nm. Morphology is predominantly spherical, although triangular, hexagonal and rod-shaped particles have been reported depending on reaction conditions. Pungam-mediated AgNPs exhibit antibacterial activity against both gram-positive and gram-negative bacteria, including *S. aureus*, *E. coli*, *B. subtilis*, *P. aeruginosa* and multidrug-resistant clinical isolates, through disruption of bacterial membranes, generation of reactive oxygen species, leakage of intracellular components, inhibition of respiratory enzymes and DNA damage (Rajeshkumar, 2016). Comparative zone-of-inhibition data across nanoparticle types are presented in Figure 4. An additional and species-specific advantage is synergy with conventional antibiotics: aqueous seed-coat extract of *P. pinnata* combined with ampicillin, meropenem, cefazolin, cefotaxime, cefpirome and cefuroxime produced 70-100% synergistic interactions against methicillin-resistant *S. aureus*, with fractional inhibitory concentration indices below 0.5 (Chusri *et al*., 2020).

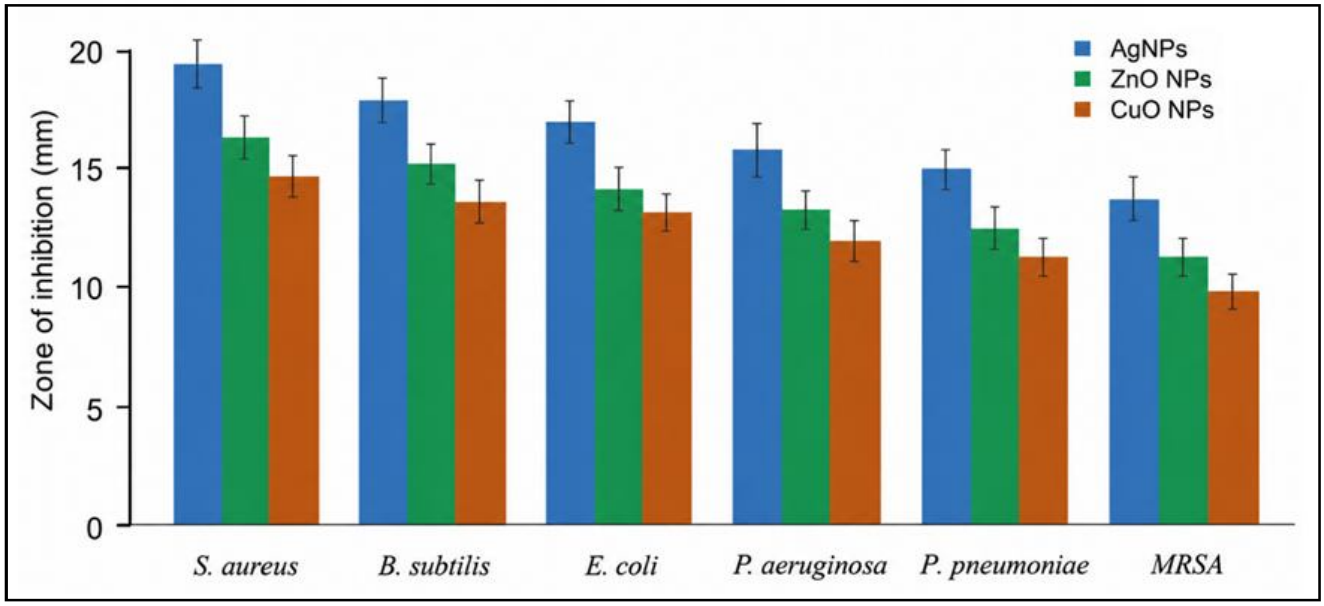


Figure 4: Comparative antibacterial activity of *P. pinnata*, expressed as zone of inhibition.

6.2 Gold nanoparticles (AuNPs)

Gold nanoparticles synthesized using Pungam leaf extract have attracted attention for their biocompatibility, chemical stability and optical properties. Khatua *et al*. (2020) reported phytosynthesis of AuNPs using *P. pinnata* leaf extract with surface plasmon resonance peaks in the 520-540 nm range and TEM-determined average sizes of 10-25 nm, among the smallest and most uniform of all Pungam-derived nanoparticles. Significantly, these AuNPs displayed fungicidal activity against oomycete isolates SR1 and BP1120 with defined MIC_{80} values, a finding of direct agricultural relevance given that oomycetes cause economically devastating crop diseases. Gold nanoparticles possess unique optical properties suiting them to biosensing, biomedical imaging, photothermal therapy and targeted drug delivery; their surfaces can be readily functionalized with antibodies, peptides, nucleic acids or phytochemicals, enabling selective accumulation within tumour tissues, while near-infrared irradiation produces localized heat that destroys cancer cells while sparing surrounding healthy tissue.

6.3 Zinc oxide nanoparticles (ZnO NPs)

Zinc oxide nanoparticles are the most thoroughly characterized metal oxide nanomaterials from this species. Sundrarajan *et al*. (2015) synthesized highly stable hexagonal-phase ZnO from leaf extract, reporting an XRD crystallite size of 26 nm, DLS size distribution spanning 10-120 nm with a mode near 90 nm, and mixed spherical, hexagonal and nanorod morphologies, with crystallization achieved at 350°C. Malaikozhundan *et al*. (2017) used seed extract to fabricate Pp-ZnO NPs of 30.4-40.8 nm, spherical in shape with wurtzite structure, which controlled Gram-positive bacterial growth at 25 µg ml^{-1} and displayed antibiofilm activity together with cytotoxicity toward MCF-7 breast cancer cells. The contrast between leaf-derived and seed-derived ZnO size distributions illustrates the decisive role of plant organ selection.

Antimicrobial activity of ZnO nanoparticles results primarily from reactive oxygen species generation, membrane disruption, zinc ion release and oxidative stress induction within microbial cells. Selective cytotoxicity toward cancer cells proceeds through mitochondrial dysfunction, DNA fragmentation and apoptosis induction. Photocatalytic activity additionally enables degradation of organic pollutants and dyes under ultraviolet irradiation. Beyond biomedicine, ZnO nanoparticles derived from related green routes have been applied as nanofertilizers, with significant growth enhancement recorded in Karanj (*P. pinnata*) seedlings themselves following foliar application (Rajiv *et al*., 2018), indicating a self-reinforcing agricultural application loop.

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

Copper and copper oxide nanoparticles synthesized using *P. pinnata* have gained attention as economical alternatives to silver because copper is abundant, inexpensive and possesses broad-spectrum antimicrobial activity. Tramta *et al.* (2024) synthesized CuO NPs from leaf aqueous extract prepared by decoction, confirming formation by a characteristic UV-Visible peak at 339 nm and determining by SEM a size range of 40.3-101.2 nm with an average of 58.1 nm; these nanoparticles were evaluated by agar disc diffusion against drug-resistant bacteria. Because metallic copper is susceptible to oxidation, CuO NPs are more commonly produced and display greater ambient stability. Their antimicrobial mechanism involves membrane damage, intracellular reactive oxygen species generation, lipid peroxidation, protein denaturation and inhibition of essential metabolic enzymes. An unusual extension of Pungam copper chemistry is the synthesis of copper nanoferrites ($CuFe_2O_4$) from leaf extract, prepared in two variants derived respectively from the unsaponifiable fraction and the methanolic extract, characterized by XRD, FTIR, EDX, DLS and SEM, and applied to catalytic oxidative decarboxylation of phenylacetic acid derivatives to benzaldehydes (Manikandan *et al.*, 2025).

6.5 Iron and iron oxide nanoparticles

Iron-based nanoparticles from *P. pinnata* have advanced notably through the isolation of pongamol as a defined single reductant. Cui *et al.* (2025) established a scalable extraction protocol at pH 5.8 followed by two-solvent recrystallization, verified product identity and isomeric integrity by UV-Visible, ^{1}H and ^{13}C NMR, LC-MS and HPLC, and then demonstrated one-pot room-temperature synthesis of colloidally stable iron nanoparticles in which purified pongamol served simultaneously as reducing agent and capping ligand. The resulting pongamol FeNPs degraded methylene blue photocatalytically and promoted *Pseudomonas defensor* growth at low concentrations. This work is methodologically important because it moves the field beyond crude-extract empiricism toward defined-molecule synthesis with reproducible stoichiometry. Iron oxide nanoparticles more broadly offer superparamagnetic behaviour enabling external magnetic field-guided drug delivery, magnetic hyperthermia and magnetic resonance imaging contrast enhancement, along with magnetic recoverability attractive for environmental remediation.

6.6 Selenium nanoparticles (SeNPs)

Selenium nanoparticles synthesized using *P. pinnata* offer superior bioavailability and reduced toxicity compared with inorganic selenium salts, which suffer from a narrow therapeutic window and dose-dependent toxicity. Behera *et al.* (2024) synthesized SeNPs from *P. pinnata* leaf extract alongside *C. sinensis* peel and *A. auriculiformis* bark in a directly comparative design, confirming formation by characteristic UV-Visible absorption and demonstrating by FTIR that plant-derived organic molecules remained adsorbed on the outer layer of the nanoparticles, evidencing successful capping. The comparative framework allowed phytochemical composition to be linked explicitly to antioxidant capacity. Selenium is an essential trace element involved in antioxidant defence, immune regulation, thyroid hormone metabolism and cellular redox homeostasis, and SeNPs enhance glutathione peroxidase activity while scavenging reactive oxygen species. Dose-dependent antioxidant and selective cytotoxic responses are illustrated in Figure 5.

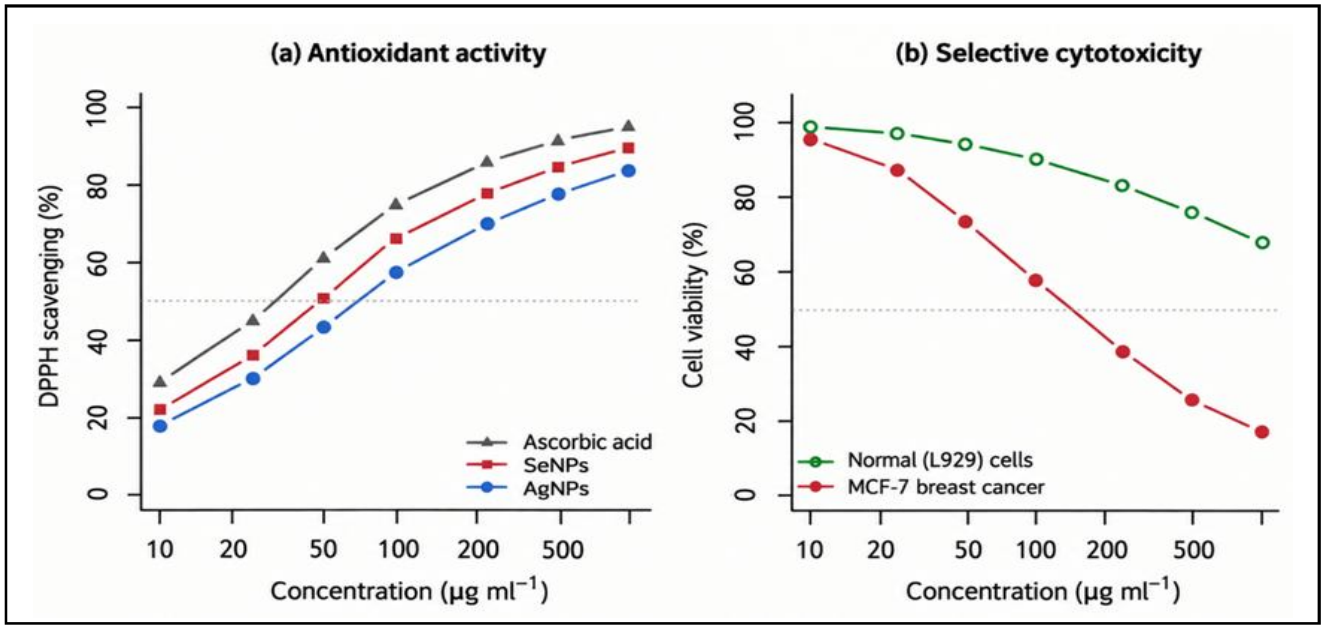


Figure 5: Dose-dependent biological activity of *P. pinnata*-mediated nanoparticles.

6.7 Titanium dioxide, trimetallic and semiconductor nanomaterials

Nithya *et al.* (2025) synthesized trimetallic Ag-Cu-TiO, nanoparticles using Pungam leaf extract, in which GC-MS-identified glycosides, flavonoids, tannins, steroids and terpenoids facilitated synthesis. XRD indicated a multiphase crystalline structure with crystallite size near 55 nm; EDX and FE-SEM confirmed a heterogeneous microstructure with elemental composition of 49.86% Ag, 31.62% Cu and 18.51% Ti by weight; and zeta potential analysis recorded -15.4 mV. These trimetallic particles achieved 81% DPPH

scavenging at 1000 µg ml^{-1} and degraded phenol red (96.47%), methyl red (83%), eosin yellow (61%) and p-nitrophenol (83.38%) within one hour, with enhanced redox activity attributed to the trimetallic composition. Separately, Pungam leaf extract has served as reducing and capping agent for pristine and erbium-doped cadmium sulfide thin films deposited by chemical bath deposition, where crystallite size fell from 19.34 nm to 6.72 nm with increasing Er doping owing to phytochemical inhibition of grain growth, and the optical bandgap proved tunable from 3.2 to 2.05 eV (Patil *et al*., 2025). Pungam leaf biowaste has also been converted into carbon dots that mediate AgNP formation for supercapacitor electrodes, achieving 540 F g^{-1} specific capacitance (Reddy *et al*., 2025).

Table 2: Nanoparticles synthesized from different parts of *P. pinnata* with reported characteristics and applications

Nanoparticle	Plant part	Major reducing phytochemicals	Typical size (nm)	Reported applications and references
Silver (AgNPs)	Dried leaves	Flavonoids, phenolics, proteins	10-40	Antibacterial (Raut *et al*., 2010)
Silver (AgNPs)	Fresh bark	Tannins, phenolics, flavonoids	5-55	Antibacterial, Gram-positive and Gram-negative (Rajeshkumar, 2016)
Silver (AgNPs)	Seeds	Karanjin, seed proteins, amide I	95-130	Wound healing, antipsoriatic nanogel (Paul and Londhe, 2019; Telange *et al*., 2024)
Gold (AuNPs)	Leaves	Flavonoids, polyphenols	10-25	Fungicidal against oomycetes; imaging (Khatua *et al*., 2020)
Zinc oxide (ZnO)	Leaves	Phenolics, flavonoids, proteins	10-120	Antibacterial, photocatalysis (Sundrarajan *et al*., 2015)
Zinc oxide (ZnO)	Seeds	Seed proteins, furanoflavonoids	30.4-40.8	Antibacterial, antibiofilm, anti-MCF-7 (Malaikozhundan *et al*., 2017)
Copper oxide (CuO)	Leaves	Polyphenols, tannins, proteins	40.3-101.2	Antibacterial against resistant strains (Tramta *et al*., 2024)
Copper nanoferrite	Leaves	Unsaponifiable and methanolic fractions	-	Catalytic oxidative decarboxylation (Manikandan *et al*., 2025)
Iron (FeNPs)	Seed oil (pongamol)	Purified pongamol	8-35	Photocatalysis, bacterial growth promotion (Cui *et al*., 2025)
Selenium (SeNPs)	Leaves	Polyphenols, proteins, amino acids	20-100	Antioxidant, comparative efficacy (Behera *et al*., 2024)
Ag-Cu-TiO_2	Leaves	Glycosides, flavonoids, tannins, steroids	40-70	Antioxidant, dye degradation catalysis (Nithya *et al*., 2025)
CdS thin films	Leaves	Flavonoids, phenolics	6.7-19.3	Photocatalysis, optoelectronics (Patil *et al*., 2025)

7. Pharmacological uses and biomedical applications

Integration of *P. pinnata* with phytonanotechnology has created a generation of multifunctional nanomaterials possessing enhanced therapeutic efficacy, good biocompatibility and, in most reported systems, reduced toxicity toward healthy tissue. During green synthesis, furanoflavonoids, flavonoids, phenolics, proteins and polysaccharides remain adsorbed on nanoparticle surfaces, forming a bioactive phytochemical corona that significantly improves biological interactions. These nanoparticles are characterized using UV-Visible spectroscopy, FTIR, XRD, SEM, TEM, DLS, zeta potential analysis, EDX and GC-MS to determine optical properties, crystalline structure, particle size, morphology, elemental composition and stability.

7.1 Drug delivery systems

Pungam-mediated nanoparticles serve as efficient nanocarriers because their phytochemical-coated surfaces enhance drug loading, improve colloidal stability, prolong circulation time and facilitate cellular uptake. The most fully developed example is the silver nanoparticle-loaded nanogel of Telange *et al*. (2024), in which seed-extract-derived AgNPs were formulated into a curcumin-diglutaric acid nanogel optimized by Box-Behnken design, achieving approximately 79.35% entrapment efficiency and evaluated for viscosity, spreadability and epidermal retention. Functionalized nanoparticles accumulate selectively within diseased tissues through passive targeting via the enhanced permeability and retention effect or active targeting using antibodies, peptides, folic acid or aptamers. Controlled release improves therapeutic efficacy by maintaining optimal drug concentrations over prolonged periods; acidic tumour microenvironments accelerate release of chemotherapeutic agents, increasing local drug concentrations while minimizing systemic exposure.

7.2 Cancer therapy

Pungam-derived nanoparticles combine the intrinsic pharmacological properties of karanjin and related furanoflavonoids with the physicochemical characteristics of nanomaterials. Seed-extract-derived ZnO nanoparticles demonstrated cytotoxicity against MCF-7 breast cancer cells alongside their antibacterial and antibiofilm effects (Malaikozhundan *et al*., 2017). Mechanistically, these nanoparticles induce apoptosis, generate reactive oxygen species, disrupt

mitochondrial membrane potential, inhibit angiogenesis, arrest cell-cycle progression and suppress metastasis. Gold nanoparticles from Pungam leaf extract exhibit photothermal conversion efficiency through localized surface plasmon resonance; following tumour accumulation, near-infrared irradiation generates temperatures exceeding 42°C, resulting in protein denaturation, membrane disruption and irreversible tumour cell death.

7.3 Antimicrobial coatings and resistance management

Healthcare-associated infections remain a major challenge because microbial colonization of medical devices leads to biofilm formation and antimicrobial resistance. Pungam-mediated silver, copper oxide, zinc oxide and titanium dioxide nanoparticles possess broad-spectrum antibacterial, antifungal and antibiofilm activities suited to antimicrobial surface engineering. Nanoparticle-coated urinary catheters, vascular catheters, orthopaedic prostheses, surgical instruments and cardiovascular implants exhibit reduced microbial colonization, with sustained release of antimicrobial metal ions providing long-term protection. The demonstrated synergy between Pungam extract and six β-lactam antibiotics against MRSA (Chusri *et al*., 2020) suggests that Pungam-derived nanoparticles may function as antibiotic adjuvants rather than standalone agents, an especially valuable role in resistance management where restoring the efficacy of existing antibiotics is often more tractable than developing new ones.

7.4 Wound healing and dermatological applications

Wound healing represents the most clinically advanced application of Pungam nanotechnology, supported by in vivo evidence rather than in vitro assays alone. Paul and Londhe (2019) incorporated seed-extract-derived AgNPs into a gel and evaluated it in an excision wound model in Wistar rats over 30 days of daily topical application, measuring wound contraction and conducting histopathological examination of healed tissue; the AgNP gel produced significant wound healing activity compared with 5% povidone-iodine ointment. Telange *et al*. (2024) extended this to inflammatory skin disease, assessing AgNP-loaded nanogel in an imiquimod-induced psoriasis rat model and demonstrating improved retention, accumulation and epidermal penetration. These nanoparticles reduce microbial contamination, modulate inflammatory responses, stimulate angiogenesis and promote fibroblast proliferation and collagen deposition.

7.5 Antidiabetic and metabolic applications

Karanjin confers a mechanistic rationale for antidiabetic nanoformulations that is specific to this species. Treatment of L6-GLUT4myc myotubes with karanjin substantially increased glucose uptake and GLUT4 translocation to the cell surface in a concentration-dependent manner without altering total GLUT4 protein or mRNA, indicating a post-translational mechanism distinct from that of common oral hypoglycaemics (Al Muqarrabun *et al*., 2013). Oral karanjin at 2 mg kg^{-1} day^{-1} for seven days significantly reduced blood glucose in alloxan-induced diabetic rats, and multireceptor computational analysis has confirmed favourable drug-likeness, ADMET properties, moderate solubility, high gastrointestinal absorption and blood-brain barrier penetration for karanjin relative to metformin, insulin, repaglinide and sitagliptin (Ryan *et al*., 2024; Noor *et al*., 2020). Nanoencapsulation of karanjinbearing extracts therefore offers a route to improving the bioavailability of an already validated antidiabetic pharmacophore.

7.6 Tissue engineering, imaging and biosensing

Pungam-mediated nanoparticles enhance scaffold bioactivity by improving mechanical strength, cellular adhesion, proliferation, differentiation and extracellular matrix deposition, while their antioxidant and anti-inflammatory properties promote tissue regeneration and minimize oxidative stress at injury sites. In diagnostic imaging, iron oxide nanoparticles exhibit superparamagnetic properties that enhance MRI contrast, and gold nanoparticles possess high X-ray attenuation coefficients making them effective computed tomography contrast agents. The phytochemical corona enhances stability while reducing toxicity and facilitating selective accumulation in diseased tissues. Pungam-derived gold and silver nanoparticles exhibit localized surface plasmon resonance properties facilitating rapid, sensitive detection of disease biomarkers, glucose, cholesterol, nucleic acids, pathogens, heavy metals and pesticides, with applications in pointofcare diagnostics, food safety and environmental monitoring.

7.7 Dental and ophthalmic applications

Pungam-derived nanoparticles exhibit activity against oral pathogens including *Streptococcus mutans*, *Porphyromonas gingivalis* and *Candida albicans*, and can be incorporated into dental composites, adhesives, root canal sealers, implant coatings and mouthwashes, inhibiting bacterial adhesion and biofilm formation without compromising mechanical properties. This application has particular cultural continuity, since Pungam roots have long been used as chewing sticks for oral hygiene in traditional Indian practice. In ophthalmology, nanoparticle formulations improve drug solubility, enhance corneal penetration, prolong ocular retention and enable sustained release, with investigations directed at bacterial keratitis, conjunctivitis, glaucoma and retinal degeneration.

8. Toxicity, biosafety and regulatory considerations

Yadav *et al*. (2025) synthesized AgNPs from methanolic leaf extract and investigated their effects in male Wistar rats, documenting antifertility activity mediated through oxidative stress and protein degradation pathways, with transmission electron microscopy revealing ultrastructural damage to reproductive tissue and biochemical analysis showing marked decreases in total protein content indicative of disrupted cellular metabolism and structural protein synthesis. While the authors frame this dual role as offering opportunity in male contraception research alongside nanomedicine, it establishes unambiguously that Pungam-derived AgNPs are biologically potent systemically and require organ-specific toxicological profiling before therapeutic deployment.

This finding sits alongside a generally favourable safety record for the parent plant: toxicity studies of extracts and isolated compounds from *P. pinnata* have generally reported no significant toxicity or organ abnormality in rodent models (Al Muqarrabun *et al*., 2013). The discrepancy illustrates a central principle of nanotoxicology, namely that the biological behaviour of a nanoparticle is not predictable from the safety profile of its botanical precursor. Comprehensive *in vivo* toxicity studies, pharmacokinetic profiling, biodistribution analyses and long-term biosafety evaluations conducted in accordance with established guidance for the safety assessment of nanomaterialsare therefore prerequisites for clinical translation. Standardization of extraction procedures, synthesis protocols and characterization methods is equally essential, since

batch-to-batch variation in phytochemical content arising from cultivar, season, geography and plant age directly propagates into nanoparticle heterogeneity.

9. Future prospects

Phytonanotechnology based on *P. pinnata* is positioned to become a significant platform for sustainable multifunctional nanomaterials, and several research directions appear especially promising. First, the defined-molecule approach pioneered for pongamol should be extended to karanjin and the wider furanoflavonoid series, replacing crude-extract empiricism with reproducible stoichiometric synthesis. Second, formal design-of-experiment optimization, following the Box-Behnken precedent, should displace one-factor-at-a-time screening. Third, advanced omics approaches including metabolomics, proteomics and transcriptomics should be deployed to identify the key biomolecules responsible for nucleation, growth and stabilization, building on the genomic and transcriptomic resources now available for this species (Sreeharsha *et al*., 2016; Kazakoff *et al*., 2012). Fourth, integration of artificial intelligence, machine learning and computational modelling offers opportunities to optimize reaction parameters, predict nanoparticle properties and accelerate rational design of customized nanoplatforms.

Underexplored organs, particularly flowers and roots, warrant systematic investigation, as does valorization of the seed cake remaining after biodiesel extraction, which represents a large, currently low-value waste stream containing residual furanoflavonoids. Development of multifunctional hybrid nanoparticles capable of simultaneous drug delivery, imaging, biosensing and therapeutic functions will expand the scope of precision medicine. Applications in gene editing, mRNA therapeutics, vaccine delivery, antimicrobial resistance management and smart diagnostic systems remain essentially unexplored for this species. Collaborative efforts among plant scientists, nanotechnologists, clinicians and regulatory agencies will be crucial for translating laboratory-scale discoveries into safe, cost-effective and commercially viable healthcare technologies.

10. Conclusion

P. pinnata has emerged as a distinctive biological resource for green nanoparticle synthesis owing to its furanoflavonoid-rich phytochemical composition and its reducing, stabilizing and capping capabilities. Pungam-mediated nanoparticles exhibit good biocompatibility, physicochemical stability and diverse biomedical activities including antimicrobial, antioxidant, anticancer, anti-inflammatory, antidiabetic, wound-healing and drug-delivery applications, with in vivo wound healing and antipsoriatic efficacy representing the most clinically advanced evidence. The species offers the strategic advantages of being non-edible, nitrogen-fixing, drought- and salinity-tolerant and cultivable on marginal land, so that scaling nanomaterial production creates no food-versus-feedstock conflict. Nevertheless, challenges relating to synthesis standardization, batch reproducibility, large-scale production, regulatory approval and comprehensive biosafety assessment must be addressed before widespread clinical implementation, and the documented reproductive toxicity of Pungam-derived silver nanoparticles in male rodents illustrates that green provenance does not guarantee biological safety. Continued interdisciplinary research integrating green chemistry, nanotechnology, biotechnology and artificial intelligence will accelerate the translation of Pungam-mediated nanomaterials into sustainable biomedical innovations.

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All data are provided within the manuscript.

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

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Conflict of interest

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

References

Ahmed, S.; Ahmad, M.; Swami, B.L. and Ikram, S. (2016). A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. Journal of Advanced Research, **7**(1):17-28.

Al Muqarrabun, L.M.R.; Ahmat, N.; Ruzaina, S.A.S.; Ismail, N.H. and Sahidin, I. (2013). Medicinal uses, phytochemistry and pharmacology of *Pongamia pinnata* (L.) Pierre: A review. Journal of Ethnopharmacology, **150**(2):395-420.

Baig, N.; Kammakakam, I. and Falath, W. (2021). Nanomaterials: A review of synthesis methods, properties, recent progress and challenges. Materials Advances, **2**(6):1821-1871.

Beg, M.; Maji, A.; Mandal, A.K.; Das, S.; Aktara, M.N.; Jha, P.K. and Hossain, M. (2017). Green synthesis of silver nanoparticles using *Pongamia pinnata* seed: Characterization, antibacterial property and spectroscopic investigation of interaction with human serum albumin. Journal of Molecular Recognition, **30**(1):e2565.

Behera, A.; Dharmalingam Jothinathan, M.K.; Ryntathiang, I.; Saravanan, S. and Murugan, R. (2024). Comparative antioxidant efficacy of green-synthesised selenium nanoparticles from *Pongamia pinnata*, *Citrus sinensis* and *Acacia auriculiformis*: An *in vitro* analysis. Cureus, **16**(4):e58439.

Biswas, B.; Scott, P.T. and Gresshoff, P.M. (2011). Tree legumes as feedstock for sustainable biofuel production: Opportunities and challenges. Journal of Plant Physiology, **168**(16):1877-1884.

Chusri, S.; Chaicoch, N.; Thongza-ard, W.; Limsuwan, S. and Voravuthikunchai, S.P. (2020). *In vitro* synergy of *Pongamia pinnata* extract in combination with antibiotics for inhibiting and killing methicillin-resistant *Staphylococcus aureus*. Journal of Traditional and Complementary Medicine, **10**(2):128-135.

Cui, R.; Wu, M.; Galang, A.; Perez, F.; Hing, V.P. and colleagues (2025). Scalable extraction of pongamol from *Pongamia pinnata* for synthesis and application of colloidally stable iron nanoparticles. RSC Advances, **15**(56):48666-48678.

Gu, Z.; Guo, Y.; Mao, X.; Qi, M. and Ge, B. (2025). Green synthesis of nanomaterials mediated by herbal medicine: Mechanism, characterization and application prospects. Natural Product Communications, **20**(8):193.

Ilavenil, K.K.; Senthilkumar, V. and Kasthuri, A. (2025). Green synthesis of metal nanoparticles from medicinal plants: Environmental and health applications. Discover Catalysis, **2**(1):3.

Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. Green Chemistry, **13**(10):2638-2650.

Kazakoff, S.H.; Imelfort, M.; Edwards, D.; Koehorst, J.; Biswas, B.; Batley, J.; Scott, P.T. and Gresshoff, P.M. (2012). Capturing the biofuel wellhead and powerhouse: The chloroplast and mitochondrial genomes of the leguminous feedstock tree *Pongamia pinnata*. PLoS ONE, **7**(12):e51687

Kesari, V.; Das, A. and Rangan, L. (2010). Physico-chemical characterization and antimicrobial activity from seed oil of *Pongamia pinnata*, a potential biofuel crop. Biomass and Bioenergy, **34**(1):108-115.

Khatua, A.; Priyadarshini, E.; Rajamani, P.; Patel, A.; Kumar, J.; Naik, A.; Saravanan, M.; Barabadi, H. and Paul, B. (2020). Phytosynthesis, characterization and fungicidal potential of emerging gold nanoparticles using *Pongamia pinnata* leave extract: A novel approach in nanoparticle synthesis. Journal of Cluster Science, **31**:125-131.

Kumar, J.; Ramlal, A.; Mallick, D. and Mishra, V. (2021). Encapsulation, release and insecticidal activity of *Pongamia pinnata* (L.) seed oil. Heliyon, **7**(3):e06585.

Lakhani, K.G; Hamid, R.; Motamedi, E. and Marviya, G.V. (2025). A review on plant metabolite-mediated nanoparticle synthesis: Sustainable applications in horticultural crops. Frontiers in Nanotechnology, **7**:1545413.

Malaikozhundan, B.; Vaseeharan, B.; Vijayakumar, S.; Pandiselvi, K.; Ali, M.R.; Kalanjiam, R.; Murugan, K. and Benelli, G. (2017). Biological therapeutics of *Pongamia pinnata* coated zinc oxide nanoparticles against clinically important pathogenic bacteria, fungi and MCF-7 breast cancer cells. Microbial Pathogenesis, **104**:268-277.

Manikandan, V.; Rajkumar, S. and Srinivasan, K. (2025). Copper nanoferrites produced by extracting the leaves of the *Pongamia pinnata* plant and their catalytic reaction in oxidative decarboxylation process. Inorganic Chemistry Communications, **172**:113705.

Mittal, A.K.; Chisti, Y. and Banerjee, U.C. (2013). Synthesis of metallic nanoparticles using plant extracts. Biotechnology Advances, **31**(2):346-356.

Narayanan, K.B. and Sakthivel, N. (2010). Biological synthesis of metal nanoparticles by microbes. Advances in Colloid and Interface Science, **156**(1-2):1-13.

Nithya, R.; Kalaiselvi, S. and Thirumalai, K. (2025). Green synthesis of Ag-Cu-TiO, trimetallic nanoparticles via *Pongamia pinnata* leaf extract and its applications. Chemical Papers, **79**:4521-4536.

Noor, A.A.M.; Othman, S.N.N.; Lum, P.T.; Mani, S.; Shaikh, M.F. and Sekar, M. (2020). Molecules of interest: Karanjin: A review. Pharmacognosy Journal, **12**(4):938-945.

Patil, S.B.; Deshmukh, R.R. and Pawar, A.U. (2025). *Pongamia pinnata*-mediated green synthesis of Er-doped CdS thin films: Enhanced photocatalysis and high-efficiency optoelectronics. Journal of Materials Science: Materials in Electronics, **36**:1284.

Paul, M. and Londhe, V.Y. (2019). *Pongamia pinnata* seed extract-mediated green synthesis of silver nanoparticles: Preparation, formulation and evaluation of bactericidal and wound healing potential. Applied Organometallic Chemistry, **33**(6):e4624.

Pavithra, K.; Rajeshkumar, S. and Venkat Kumar, S. (2016). Phytochemical screening and bioactive potential of *Pongamia pinnata* extracts. International Journal of Pharma and Bio Sciences, **7**(4):112-119.

Pulipati, S.; Babu, P.S.; Lakshmi, D.N.; Navyasri, N.; Harshini, Y.; Vyshnavi, J. and Prasanth, M. (2018). A phyto pharmacological review on a versatile medicinal plant: *Pongamia pinnata* (L.) Pierre. Journal of Pharmacognosy and Phytochemistry, **7**(4):478-585.

Rajeshkumar, S. (2016). Synthesis of silver nanoparticles using fresh bark of *Pongamia pinnata* and characterization of its antibacterial activity against gram positive and gram-negative pathogens. Resource-Efficient Technologies, **2**(1):30-35.

Rajiv, P.; Bavadharani, B.; Kumar, M.N. and Vanathi, P. (2018). Biosynthesis of zinc oxide nanoparticles using leaf extract of *Calotropis gigantea*: Characterization and its evaluation on tree seedling growth in nursery stage. Applied Nanoscience, **8**:1179-1187.

Rani, N.; Singh, P.; Kumar, S.; Kumar, P.; Bhankar, V. and Kumar, K. (2023). Plant-mediated synthesis of nanoparticles and their applications: A review. Materials Research Bulletin, **163**:112233.

Raut, R.W.; Kolekar, N.S.; Lakkakula, J.R.; Mendhulkar, V.D. and Kashid, S.B. (2010). Extracellular synthesis of silver nanoparticles using dried leaves of *Pongamia pinnata* (L.) Pierre. Nano-Micro Letters, **2**(2):106-113.

Reddy, K.R.; Naik, S.J. and Kumar, P.S. (2025). Synthesis of biowaste-derived carbon-dot-mediated silver nanoparticles and the evaluation of electrochemical properties for supercapacitor electrodes. ACS Omega, **10**(24):25891-25902.

Ryan, N.M.; Jayaraman, S.; Sekar, D. and Vishnupriya, V. (2024). Multireceptor analysis for evaluating the antidiabetic efficacy of karanjin: A computational approach. Chemistry and Biodiversity, **21**(7):e202400558.

Shahzadi, S.; Fatima, S.; Ain, Q.U.; Shafiq, Z. and Janjua, M.R.S.A. (2025). Green synthesis of silver nanoparticles using plant extracts: Advances in photocatalysis, environmental remediation and biomedicine. RSC Advances, **15**(7):3858-3903.

Singh, R.; Meena, A.K. and Sharma, K. (2016). Karanja leaf: A pharmacognostical and phytochemical analysis. Journal of Pharmacognosy and Phytochemistry, **5**(5):202-206.

Sreeharsha, R.V.; Mudalkar, S.; Singha, K.T. and Reddy, A.R. (2016). Unravelling molecular mechanisms from floral initiation to lipid biosynthesis in a promising biofuel tree species, *Pongamia pinnata* using transcriptome analysis. Scientific Reports, **6**:34315.

Sundrarajan, M.; Ambika, S. and Bharathi, K. (2015). Plant-extract mediated synthesis of ZnO nanoparticles using *Pongamia pinnata* and their

activity against pathogenic bacteria. Advanced Powder Technology, **26**(5):1294-1299.

Telange, D.R.; Mahajan, N.M.; Mandale, T.; More, S. and Warokar, A. (2024).*Pongamia pinnata* seed extract-mediated green synthesis of silver nanoparticle loaded nanogel for estimation of their antipsoriatic properties. Bioprocess and Biosystems Engineering, **47**(8):1409-1431.

Tramta, P.; Rakholiya, K. and Kaneria, M. (2024). Biosynthesis of copper oxide nanoparticles formation from *Pongamia pinnata* (L.) Pierre leaf metabolites and their antibacterial activity. Research Journal of Nanoscience and Nanotechnology, **14**(1):1-7.

Usharani, K.V.; Naik, D. and Manjunatha, R.L. (2019).*Pongamia pinnata* (L.): Composition and advantages in agriculture - A review. Journal of Pharmacognosy and Phytochemistry, **8**(3):2181-2187.

Vanga, S. and Satla, S.R. (2025). A review on green synthesis, characterization and applications of plant mediated metal nanoparticles. Next Research, **2**(2):100356.

Yadav, P.; Bharti, N. and Mali, P.C. (2025). Green synthesis of silver nanoparticles using *Pongamia pinnata* methanolic extract and their antifertility impact on male rats: A TEM study. Biological Trace Element Research, **204**(3):1745-1760.

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