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Green-synthesized nanoparticles: Mechanisms, characterization, challenges and future perspectives

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Abstract
The synthesis of nanoparticles (NPs) using green chemistry principles has emerged as a transformative approach in nanotechnology, offering a sustainable alternative to conventional physical and chemical fabrication routes that rely on hazardous reagents and energy-intensive processing. This review synthesises current knowledge on the synthesis, characterization, and application of green-synthesized nanoparticles, with particular emphasis on plant, microbe, and biomolecule-mediated routes. Phytochemicals such as flavonoids, terpenoids, and phenolic compounds act as natural reducing and capping agents, yielding nanoparticles with enhanced biocompatibility, stability, and antimicrobial efficacy while minimising toxic by-products and energy consumption. Particular attention is given to nanoparticles derived from forest and agroforestry species including neem (*Azadirachta indica*), *Jatropha curcas*, *Lantana camara*, *Swietenia mahagoni*, *Syzygium aromaticum*, and *Terminalia catappa* which illustrate the breadth of biogenic precursors available for sustainable nanomaterial fabrication. The review further examines the physicochemical factors governing nanoparticle formation, contrasts top-down, bottom-up, and biological synthesis strategies, and summarises the principal techniques used for nanoparticle characterization. The wide-ranging applications of green nanotechnology in medicine, agriculture, environmental remediation, energy, textiles, and food packaging are discussed alongside the persistent challenges of process standardisation, mechanistic understanding, industrial scale-up, and nanotoxicology. Addressing these gaps through interdisciplinary research will be essential to realising the full potential of green-synthesized nanoparticles as a cornerstone for the development of sustainable nanotechnology across biomedical, agricultural, environmental, and industrial sectors.

Keywords: Green synthesis, nanoparticles, green chemistry, biogenic synthesis, biogenic nanomaterials, sustainable nanotechnology

1. Introduction
Nanoscience and nanotechnology have emerged as transformative disciplines at the interface of physics, chemistry, biology, and materials science, addressing critical challenges across a wide range of scientific and industrial sectors (Ozin and Arsenault, 2015) [30]. Nanoparticles (NPs) are materials with at least one dimension between 1 and 100 nanometres occupy the intermediate space between bulk materials and atomic or molecular structures, and this scale confers a distinctive combination of physical, chemical, and optical properties not observed in either extreme (Thakkar *et al*., 2010) [42]. This unique behaviour has driven a rapid expansion of nanoparticle research, with considerable attention devoted to both the mechanisms of their synthesis and the breadth of their applications.

Nanoparticles are broadly classified as inorganic or organic. Inorganic nanoparticles include semiconductor materials such as zinc oxide (ZnO), zinc sulfide (ZnS), and cadmium sulfide (CdS); metallic nanoparticles such as gold (Au), silver (Ag), copper (Cu), and aluminium (Al); and magnetic nanoparticles such as cobalt (Co), iron (Fe), and nickel (Ni). Organic nanoparticles typically comprise carbon-based materials such as fullerenes, quantum dots, and carbon nanotubes. Among these, noble metal nanoparticles particularly gold and silver have attracted considerable interest owing to their exceptional chemical stability, conductivity, and antimicrobial activity (Vadlapudi and Kaladhar, 2014) [45]. Nanoparticle synthesis is conventionally achieved through physical (top-down) or chemical (bottom-up) methods.

Physical approaches reduce bulk materials into nanoscale structures but demand high energy inputs and generate substantial material waste, rendering them environmentally and economically unsustainable (Botes and Cloete, 2010) [6]. Chemical methods, in which nanoscale building blocks self-assemble into ordered structures, allow better control over particle size and uniformity but remain largely confined to laboratory-scale application, and tailoring nanoparticles with specific structural and functional properties continues to pose a significant scientific challenge (Wu *et al*., 2012 [50]; Zeng *et al*., 2008) [52].

Because conventional synthesis methods often involve hazardous chemicals and energy-intensive processing, researchers have increasingly turned to green chemistry as a sustainable alternative. Green synthesis exploits biological systems plants, microorganisms, and natural product extracts to produce nanoparticles under mild, eco-friendly conditions, and has proven particularly effective for metal and metal-oxide nanoparticles while minimising environmental impact (Thema *et al*., 2015) [43]. Although the idea of using biological entities to reduce metal precursors dates back to the nineteenth century, the precise mechanisms governing these processes remain incompletely understood. Interest in green synthesis has grown steadily because it relies on natural reducing, capping, and stabilising agents, eliminating the need for toxic, energy-intensive, and costly reagents (Korbekandi *et al*., 2009 [23]; Arumugam *et al*., 2015) [4]. Plant-derived phenolics, flavonoids, and terpenoids substitute for conventional reducing agents, minimising chemical contamination (Chandran *et al*., 2006 [8]; Huang *et al*., 2007) [16], improving cost-effectiveness (Mittal *et al*., 2013) [25], and enhancing overall sustainability (Iravani, 2011) [17]. Green synthesis additionally enables the recovery of precious metals such as gold and silver from industrial waste streams, addressing resource scarcity and price volatility (Wang *et al*., 2009) [49]. Biomolecules such as proteins, enzymes, and polysaccharides not only stabilise the resulting nanoparticles but also enhance their biocompatibility and antimicrobial efficacy by promoting interaction with microbial cell surfaces (Botes and Cloete, 2010) [6]. Taken together, these attributes make green synthesis a scalable, industrially adaptable strategy that advances nanotechnology as a tool for addressing pressing challenges in medicine, agriculture, and energy while minimising environmental impact.

2. Origin and Evolution of Nanotechnology

Nanotechnology, operating at scales unimaginably minute, has driven a revolution in science and technology. Derived from the Greek word "nanos", denoting smallness, the field involves the deliberate manipulation of matter at the atomic, molecular, and macromolecular scale (Paul *et al*., 2023) [31]. Its conceptual origin is generally traced to Richard Feynman's seminal 1959 lecture "There's Plenty of Room at the Bottom", in which he envisioned humanity's capacity to manipulate matter atom by atom. Although the idea initially received a muted response, it gained substantial traction during the 1980s with the advent of instruments capable of imaging and manipulating individual atoms, laying the foundation for the field recognised today as nanotechnology.

Nanoscience is inherently interdisciplinary, drawing on physics, chemistry, engineering, biology, mathematics, agriculture, and forestry, and this collaborative character continues to drive innovation across sectors. From quantum dots and carbon nanotubes to nanocomposites and biomimetic materials, the field has unlocked novel materials with properties and applications unattainable at the bulk scale (Paul *et al*., 2023) [31], with profound implications for electronics, healthcare, energy, and environmental conservation.

3. Green Chemistry and the Emergence of Green Nanotechnology

Green chemistry represents a fundamental shift in how chemical products and processes are designed, placing environmental sustainability and human health at the centre of chemical practice. Its twelve guiding principles provide a framework for minimising the environmental impact of chemical activity while optimising efficiency and safety. The convergence of nanotechnology and green chemistry has given rise to green nanotechnology, an interdisciplinary field that seeks to develop environmentally sustainable nanomaterials, processes, and applications (Begum *et al*., 2022) [5]. By incorporating green chemistry principles waste prevention, the use of benign solvents, and the design of inherently safer chemicals can be achieved. green nanotechnology aims to harness the unique properties of nanomaterials while safeguarding human health and the environment across a wide range of application sectors.

4. Mechanism of Green Nanoparticle Synthesis

4.1 General Reaction Mechanism

When plant extracts are combined with metal precursor salts, a cascade of chemical transformations gives rise to nanoparticle formation. Plant extracts obtained from stems, leaves, flowers, roots, or seeds contain a rich array of phytochemicals like alcohols, aldehydes, phenols, and flavonoids that possess intrinsic reducing capacity (Amrita *et al*., 2015) [2]. During the reaction, these phytochemicals donate electrons to reduce metal ions (M^+) to their zero-valent state (M^0); the resulting metal atoms then undergo nucleation, and subsequent atom-by-atom addition drives particle growth (the classical LaMer nucleation-and-growth model). As nucleation and growth proceed, biomolecules present in the extract simultaneously adsorb onto the newly formed nanoparticle surface, a process known as capping. Capping arrests further growth, prevents agglomeration, and confers colloidal stability, ultimately determining the size and shape of the mature nanoparticle. This reduction-nucleation-capping sequence typically proceeds under mild conditions ambient temperature and pressure distinguishing green synthesis from conventional routes that often require elevated temperature, pressure, or strong reducing agents. Reaction parameters such as extract and precursor concentration, pH, temperature, and incubation time govern the balance between nucleation and growth, and therefore the final size, shape, and yield of the nanoparticles produced (Nagar and Devra, 2018) [26]; careful optimisation and standardisation of these parameters is essential for reproducible synthesis.

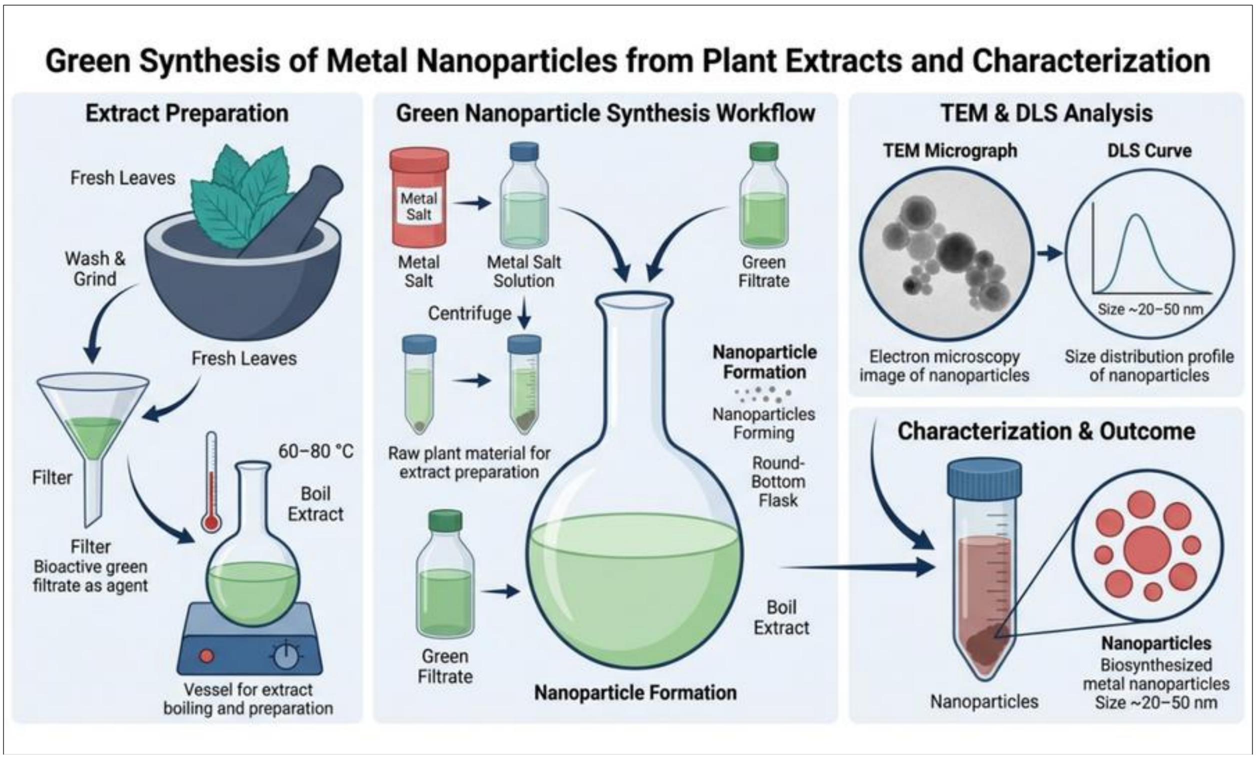


Fig 1: Schematic illustration of green synthesis of metal nanoparticles from plant extracts and their characterization.

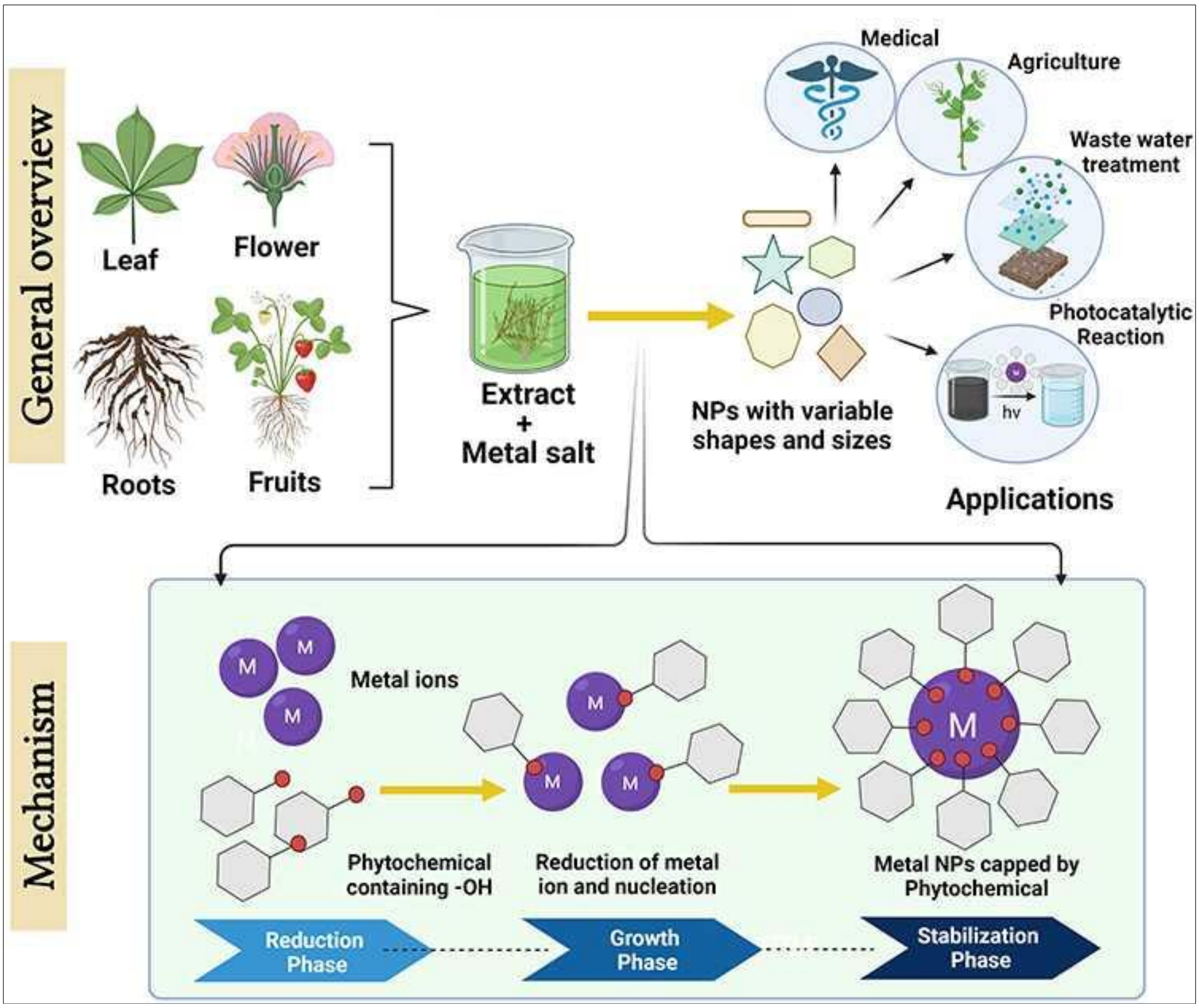


Fig 2: General overview and mechanism of green nanoparticle synthesis (Singh *et al*., 2023) [38]

The onset of nanoparticle formation is frequently visible to the naked eye: as free metal ions are reduced and coalesce into nanoscale clusters, the delocalised conduction electrons at the particle surface begin to oscillate collectively in resonance with incident light a phenomenon known as surface plasmon resonance (SPR). This produces the characteristic colour changes (for example, colourless to ruby-red for gold nanoparticles, or pale yellow to brown for silver nanoparticles) that are commonly used as a first, qualitative indicator of successful synthesis, and which are subsequently confirmed and quantified by UV-visible spectrophotometry (Section 6). Once nucleation is complete, particle populations continue to evolve through Ostwald ripening, whereby smaller, thermodynamically less stable nuclei dissolve and redeposit onto larger particles, gradually broadening or narrowing the size distribution depending on the strength and coverage of the capping layer. Colloidal stability of the final nanoparticles is thus governed by two complementary mechanisms: electrostatic stabilisation, arising from charged functional groups (e.g., carboxylate or hydroxyl groups) adsorbed on the nanoparticle surface, which is commonly assessed via zeta-potential measurement; and steric stabilisation, in which bulky biomolecules such as proteins and polysaccharides physically hinder particle-particle approach. Because both mechanisms operate simultaneously in most plant-mediated systems, green-synthesized nanoparticles frequently display superior long-term colloidal stability relative to nanoparticles produced by purely chemical reduction, where a single capping agent is typically used.

Relative to conventional chemical or physical synthesis, green synthesis offers several distinct advantages: it is cost-effective, relies on readily available plant material, and avoids hazardous chemicals and solvents. It is also socially acceptable, aligning with public concern for environmental protection and sustainable practice. These attributes make green synthesis a holistic, low-impact route to functional nanomaterials, combining cost-effectiveness, environmental compatibility, and social acceptability (Saranyaadevi *et al*., 2014) [37].

4.2 Factors Governing Nanoparticle Synthesis

The size, shape, composition, and functional properties of green-synthesized nanoparticles are governed by a set of interacting physicochemical and procedural factors, summarised in Table 1.

Table 1: Principal factors governing green nanoparticle synthesis

Factor	Influence on nanoparticle synthesis
Precursor selection	Determines the elemental composition and, indirectly, the crystal structure of the nanoparticles formed.
Reaction conditions (temperature, pH, time)	Govern reaction kinetics and thermodynamics; strongly influence nucleation rate, particle size, and yield.
Stabilising / capping agents	Prevent agglomeration and stabilise the colloidal dispersion; may be polymers, surfactants, or biomolecules.
Solvent choice	Affects reactant solubility, reaction kinetics, and final nanoparticle morphology.
Reaction mechanism	Nucleation-growth, aggregation, and reduction pathways differ with precursor chemistry and conditions.
Agitation and mixing	Promotes uniform reactant distribution and consistent particle formation.
Concentration ratios	Relative concentrations of reactant, extract, and stabiliser determine size, morphology, and stability.

By systematically controlling these variables, researchers can tailor nanoparticle synthesis for specific downstream applications in electronics, catalysis, biomedical devices, and environmental remediation (Sagar *et al*., 2023) [34].

5. Approaches to Nanoparticle Synthesis: Nanoparticle fabrication is broadly achieved through three complementary strategies: top-down, bottom-up, and biological (green) synthesis (Velmurugan *et al*., 2011) [47].

5.1 Top-Down Approach: The top-down approach breaks bulk material down into nanoscale particles, analogous to sculpting a large block into fine figurines. Representative techniques are summarised in Table 2.

Table 2: Representative top-down nanoparticle synthesis techniques

Technique	Description
Mechanical / ball milling	High-energy grinding progressively pulverises bulk material into nanoscale particles.
Lithographic methods	Light or electron beams etch nanoscale patterns onto a surface, akin to a precision stencil.
Sputtering	A target material is bombarded with high-energy ions, ejecting atoms that condense into nanoparticles.
Laser ablation	A pulsed laser removes material from a target, generating nanoparticles in vapour or liquid suspension.

5.2 Bottom-Up Approach

The bottom-up approach assembles nanoparticles from atomic or molecular precursors, similar to building with Lego bricks, and offers greater control over size, shape, and composition (Table 3).

Table 3: Representative bottom-up nanoparticle synthesis techniques

Technique	Description
Chemical vapour deposition (CVD)	A gaseous precursor decomposes within a reaction chamber, depositing nanoparticles onto a substrate.
Sol-gel process	A liquid sol transforms into a gel containing nanoparticles, analogous to suspending fine particles within a jelly-like matrix.
Pyrolysis	A precursor is thermally decomposed at high temperature to yield nanoparticles.

5.3 Biological (Green) Approach

Biological methods employ plant extracts, bacteria, fungi, algae, or isolated biomolecules to reduce metal ions and form nanoparticles. This eco-friendly strategy exploits the intrinsic reducing capacity of biomolecules present in biological systems to yield nanoparticles of controlled size and shape without recourse to hazardous chemicals. While plant-mediated synthesis (detailed in Section 7) is the most extensively studied route because of its simplicity, speed, and single-step processing, microorganisms and isolated biomolecules represent complementary and, in some respects, more precisely controllable biological platforms.

Microbial synthesis is generally classified as intracellular or extracellular. In intracellular synthesis, metal ions are transported into the microbial cell, where they are reduced by intracellular enzymes and accumulate within the cytoplasm or periplasmic space; this route typically yields nanoparticles of high monodispersity but requires additional downstream processing (cell lysis and purification) to recover the product. In extracellular synthesis, by contrast, the cell secretes reductase enzymes and stabilising proteins into the surrounding medium, so that nanoparticle formation occurs outside the cell; this route is generally preferred for scale-up because the nanoparticles can be harvested directly from the culture filtrate without cell disruption. Fungi are particularly well suited to extracellular synthesis owing to their prolific secretion of extracellular enzymes and their tolerance of relatively high metal-ion concentrations, while bacteria and cyanobacteria have been widely explored for both intracellular and extracellular routes. Algae both micro- and macroalgae, additionally offer polysaccharides, pigments, and structural proteins that function as efficient reducing and capping agents, and are attracting growing interest because of their fast growth rates and amenability to large-scale cultivation. A parallel strategy uses isolated, purified biomolecules (enzymes, proteins, or polysaccharides) directly as cell-free reducing/capping systems; this biomimetic approach sacrifices some of the cost advantage of whole-organism synthesis but offers superior batch-to-batch reproducibility, since it removes the variability associated with cell physiology and growth stage. Table 4 summarises these complementary biological synthesis platforms.

Table 4: Microorganism and biomolecule mediated platforms for green nanoparticle synthesis

Biological agent	Mode of synthesis	Representative biomolecules	Typical nanoparticles
Bacteria (e.g., *Bacillus*, *Pseudomonas*, *Lactobacillus* spp.)	Intracellular and extracellular	Nitrate/nitrite reductase enzymes, peptides	Ag, Au, ZnO
Fungi (e.g., *Fusarium*, *Aspergillus*, *Trichoderma* spp.)	Predominantly extracellular	Secreted reductase enzymes, mycelial proteins	Ag, Au, TiO_2
Algae (micro- and macroalgae)	Extracellular	Polysaccharides, pigments, structural proteins	Ag, Au, ZnO
Yeast	Extracellular / periplasmic	Reductase enzymes	Ag, CdS
Isolated biomolecules (cell-free)	Biomimetic, cell-free reduction	Purified enzymes, proteins, polysaccharides	Ag, Au

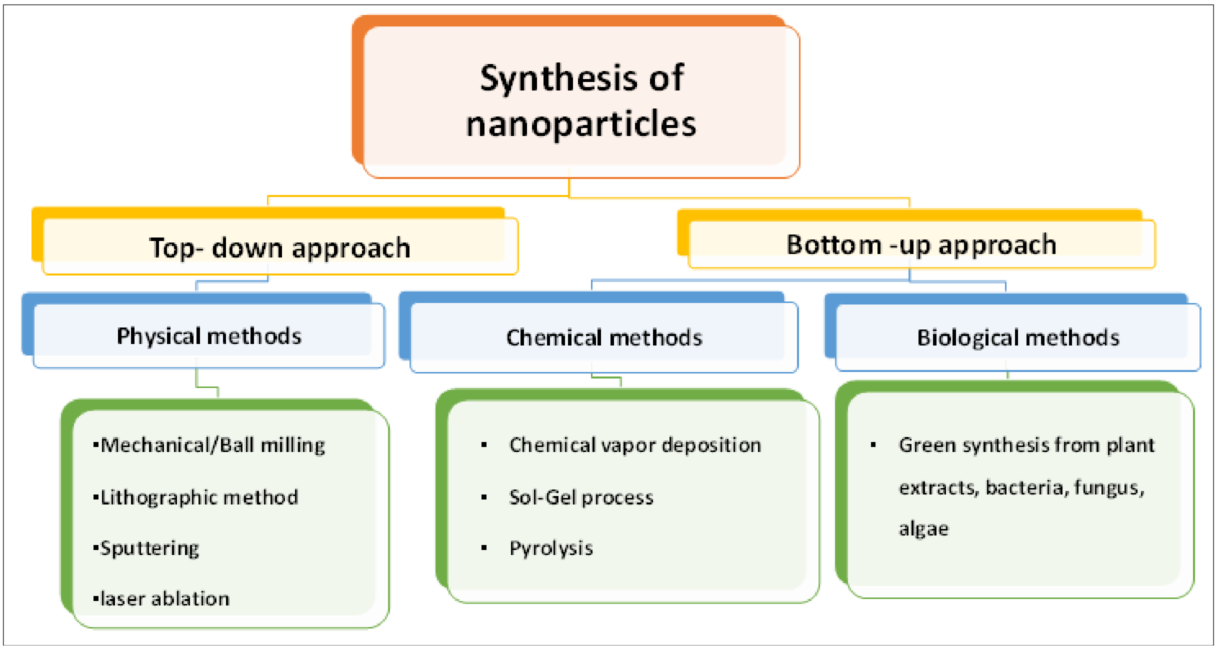
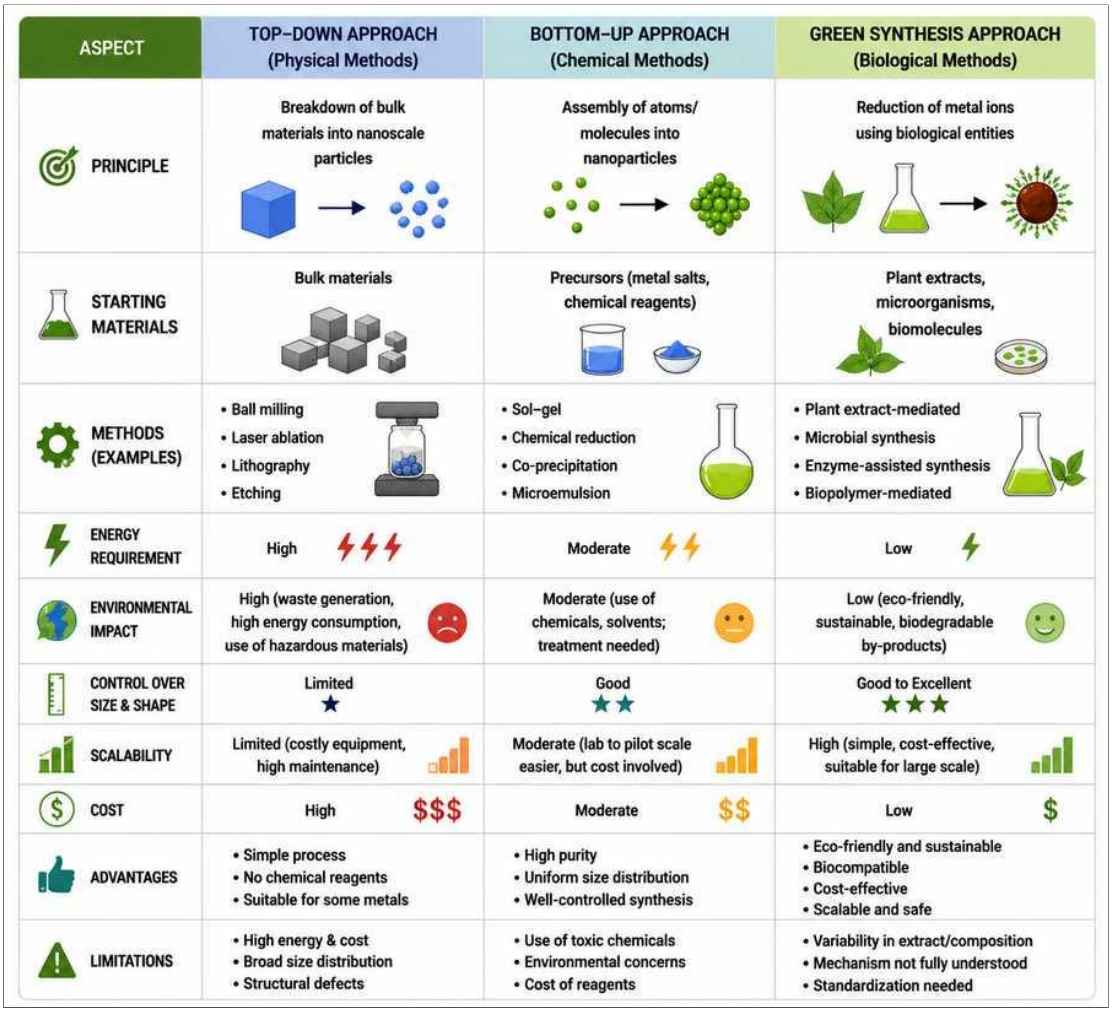


Fig 3: Comparative overview of top-down, bottom-up, and biological approaches for nanoparticle synthesis

Table 5: Comparative evaluation of top-down, bottom-up, and biological (green) synthesis strategies

Criterion	Top-down	Bottom-up	Biological / Green
Energy demand	High	Moderate-high	Low (ambient conditions)
Control over size/shape	Moderate	High	Moderate, improving with optimisation
Use of hazardous reagents	Low-moderate	Often high	Minimal to none
Cost	High (equipment-intensive)	Moderate-high	Low
Scalability	Industrial, established	Laboratory to pilot scale	Emerging; scale-up under development
Environmental impact	Significant waste generation	Solvent/reagent waste	Low; biodegradable by-products



ASPECT	TOP-DOWN APPROACH (Physical Methods)	BOTTOM-UP APPROACH (Chemical Methods)	GREEN SYNTHESIS APPROACH (Biological Methods)
PRINCIPLE	Breakdown of bulk materials into nanoscale particles	Assembly of atoms/ molecules into nanoparticles	Reduction of metal ions using biological entities
STARTING MATERIALS	Bulk materials	Precursors (metal salts, chemical reagents)	Plant extracts, microorganisms, biomolecules
METHODS (EXAMPLES)	• Ball milling • Laser ablation • Lithography • Etching	• Sol-gel • Chemical reduction • Co-precipitation • Microemulsion	• Plant extract-mediated • Microbial synthesis • Enzyme-assisted synthesis • Biopolymer-mediated
ENERGY REQUIREMENT	High	Moderate	Low
ENVIRONMENTAL IMPACT	High (waste generation, high energy consumption, use of hazardous materials)	Moderate (use of chemicals, solvents; treatment needed)	Low (eco-friendly, sustainable, biodegradable by-products)
CONTROL OVER SIZE & SHAPE	Limited ★	Good ★★	Good to Excellent ★★★
SCALABILITY	Limited (costly equipment, high maintenance)	Moderate (lab to pilot scale easier, but cost involved)	High (simple, cost-effective, suitable for large scale)
COST	High $$$	Moderate $$	Low $
ADVANTAGES	• Simple process • No chemical reagents • Suitable for some metals	• High purity • Uniform size distribution • Well-controlled synthesis	• Eco-friendly and sustainable • Biocompatible • Cost-effective • Scalable and safe
LIMITATIONS	• High energy & cost • Broad size distribution • Structural defects	• Use of toxic chemicals • Environmental concerns • Cost of reagents	• Variability in extract/composition • Mechanism not fully understood • Standardization needed

Fig 4: Comparison of top-down, bottom-up, and green synthesis approaches for nanoparticle production

6. Characterization of Green-Synthesized Nanoparticles

Because their properties are strongly size- and shape-dependent, green-synthesized nanoparticles require a battery of complementary analytical techniques for reliable characterization (Table 6). No single technique is sufficient: spectroscopic methods (UV-Vis, FTIR) confirm formation and surface chemistry, diffraction and microscopy methods (XRD, SEM, TEM) resolve crystal structure and morphology, and scattering/electrokinetic methods (DLS, zeta potential) describe colloidal behaviour in suspension the property most relevant to storage stability and biological performance. Used in combination, these methods provide a comprehensive picture of nanoparticle morphology, composition, and behaviour, enabling researchers to optimise synthesis protocols and tailor nanoparticle properties for specific applications in medicine, electronics, catalysis, and environmental remediation (Paul *et al.*, 2023) [31].

Table 6: Principal analytical techniques used to characterize green-synthesized nanoparticles

Technique	Principle	Information obtained
UV-Visible spectrophotometry	Absorption/transmission of UV-visible light, exploiting surface plasmon resonance in metal NPs	Preliminary, rapid confirmation of NP formation; concentration trends; optical/plasmonic properties
Fourier-transform infrared spectroscopy (FTIR)	Infrared absorption by molecular vibrations of capping biomolecules	Surface functional groups; identity of phytochemicals/biomolecules involved in reduction and capping
X-ray diffraction (XRD)	Diffraction of X-rays by the crystal lattice	Crystal phase, crystallinity, and crystallite size (via the Scherrer equation)
Scanning electron microscopy (SEM)	Surface scanning with a focused electron beam	Surface morphology, aggregation state, and size distribution
Transmission electron microscopy (TEM)	Electron transmission through ultrathin samples	Internal morphology, precise particle size, shape, and lattice fringes at sub-nanometre resolution
Energy-dispersive X-ray spectroscopy (EDX/EDS)	Characteristic X-rays emitted under electron-beam excitation	Elemental composition and confirmation of metal reduction
Dynamic light scattering (DLS)	Analysis of Brownian-motion-induced light scattering in suspension	Hydrodynamic diameter, polydispersity index, and colloidal stability in the dispersion medium
Zeta potential analysis	Electrophoretic mobility of charged particles in an applied field	Surface charge and electrostatic contribution to colloidal (dispersion) stability

A useful practical distinction is that TEM and XRD report the 'dry', solid-state crystalline core size, whereas DLS reports the larger hydrodynamic diameter of the particle together with its adsorbed biomolecular corona and solvation shell; discrepancies between these two size estimates are expected and, when interpreted correctly, provide indirect evidence of the thickness of the capping layer.

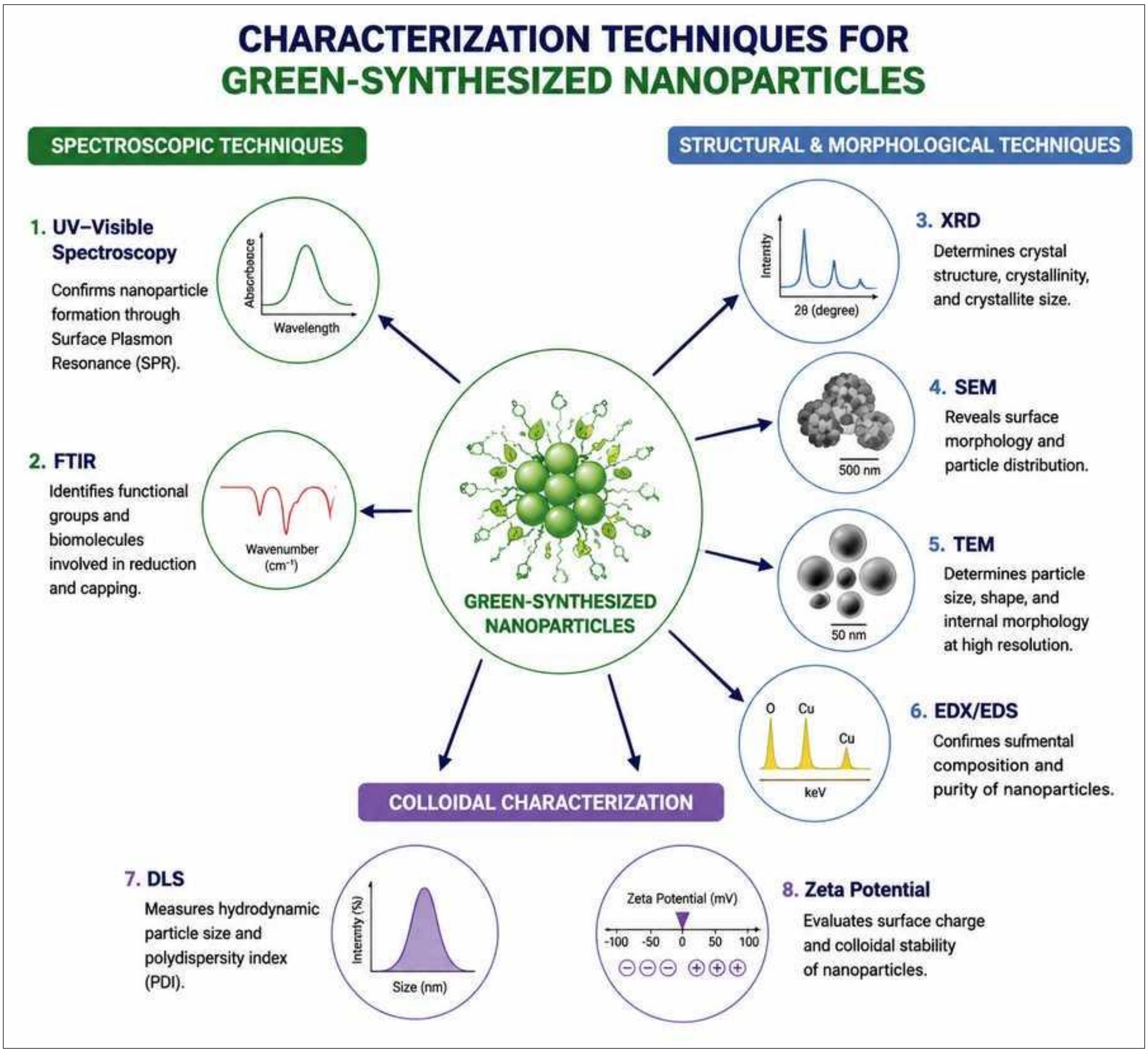


Fig 5: Characterization techniques used for the analysis of green-synthesized nanoparticles

7. Plant-Mediated Synthesis of Nanoparticles

Plant-mediated synthesis exploits the natural reducing and stabilising capacity of plant extracts for nanoparticle fabrication. The approach involves selecting suitable plant material, preparing an aqueous or solvent-based extract, and reacting the extract rich in phytochemicals with a metal-ion precursor solution. Because the reduction and capping of nanoparticles proceed under mild conditions, the process is inherently environmentally friendly and cost-effective (Raju *et al*., 2012) [33].

7.1 Green Synthesis from Neem (*Azadirachta indica*)

Components: Different parts of the neem tree leaves, seeds, bark, and derived extracts have all been used for nanoparticle synthesis. Neem tissues are rich in bioactive polyphenols, flavonoids, and terpenoids, notably azadirachtin, which act as reducing and stabilising agents. Extraction is typically performed with water or ethanol, after which the extract is combined with a metal-salt solution (commonly containing silver, gold, or copper ions); reduction under controlled temperature and pH then yields the corresponding nanoparticles (Table 7).

Table 7: Nanoparticles synthesized from different neem (*Azadirachta indica*) components

Neem component	Active ingredient	Nanocarrier / NP	Particle size (nm)	Potential application	Reference
Neem bark	Azadirachtin	Carboxymethyl-chitosan carrier	200-500	Insecticide	Feng and Peng, 2012 [14]
Neem seed kernels	Azadirachtin	Nano-emulsion	1-5	Pesticide, effective against Zabrotes subfasciatus	da Costa *et al*., 2014 [10]
Neem oil	Azadirachtin	Silica NPs	~20	Insecticidal activity against Tuta absoluta	El-Samahy *et al*., 2014 [11]
Neem leaves	Azadirachtin	Ag NPs	~100	Antifungal activity against *Aspergillus* terreus	Choudhury *et al*., 2016 [9]

7.2 Green Synthesis from Other Forest Species

Beyond neem, several forest and agroforestry species have been explored for nanoparticle biosynthesis, including *Jatropha curcas*, *Lantana camara*, *Swietenia mahagoni*, *Syzygium aromaticum* (clove), and *Terminalia catappa*. Each species contributes a distinctive phytochemical profile for example, azadirachtin in neem and curcacycline A in *Jatropha curcas* that governs reduction and stabilisation. *Azadirachta indica* extract, for instance, has been used to synthesise gold nanoparticles ranging from 2 to 100 nm (Table 8). These forest-derived synthesis routes represent environmentally sustainable alternatives to conventional fabrication, with promising applications in medicine, agriculture, and catalysis; further work to optimise these processes and identify novel forest-based precursors is warranted.

Table 8: Nanoparticles synthesized from other forest and agroforestry species

Sl. No.	Plant species	Biomolecules involved	Nanoparticle	Size	Reference
1	*Azadirachta indica*	Azadirachtin	Au	2-100 nm	Thirumurugan *et al*., 2017 [44]
2	*Lantana camara*	Carbohydrates, glycosides, flavonoids	Ag	12.55 nm	Sivakumar *et al*., 2012 [40]
3	*Swietenia mahagoni*	Polyhydroxy limonoids	Ag, Au & Au-Ag alloy	23.7 nm	Smitha *et al*., 2019 [41]
4	*Syzygium aromaticum*	Flavonoids	Au	5-100 nm	Elbagory *et al*., 2022 [13]
5	*Terminalia catappa*	Hydrolysable tannins	Au	10-35 nm	Ankamwar, 2010 [3]

8. Applications of Green Nanotechnology

Over the past decade, research output on nanotechnology has expanded dramatically, and green-synthesized nanomaterials have emerged as a cornerstone of this growth. Green nanotechnology, the environmentally benign synthesis and application of nanoparticles in support of sustainable development has demonstrated significant promise in medicine, clinical diagnostics, agriculture, environmental remediation, energy, materials science, and food technology (Gunalan *et al*., 2012; Khan and Ahmad, 2013; Jayalakshmi and Yogamoorthi, 2014; Arumugam *et al*., 2015; Kargar *et al*., 2015; Yadava *et al*., 2025) [15, 22, 18, 4, 21, 51].

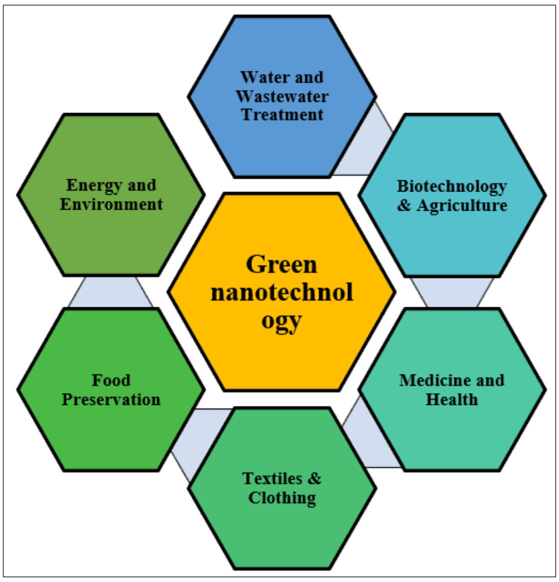


Fig 6: Application of green nanotechnology

8.1 Biomedical and Pharmaceutical Applications

Green-synthesized nanoparticles exhibit potent antibacterial, antifungal, and antiparasitic activity, arising from mechanisms such as cell wall and membrane disruption, generation of reactive oxygen species, and induction of oxidative stress, culminating in microbial cell death (Jayaseelan *et al*., 2012 [19]; Rajakumar *et al*., 2012 [32]; Acharyulu *et al*., 2014 [1]; Naika *et al*., 2015 [27]; Chaloupka *et al*., 2010) [7]. Their efficacy extends to fungal infections (Sanghi and Verma, 2009) [35] and parasitic diseases (Velayutham *et al*., 2012) [46], underscoring a broad-spectrum therapeutic potential relevant to drug delivery, wound care, and diagnostic imaging.

8.2 Environmental Remediation

Green nanotechnology offers transformative solutions for environmental clean-up, including the treatment of hazardous waste sites and the remediation of surface water, groundwater, and wastewater contaminated with toxic metal ions, organic and inorganic solutes, and microorganisms (Njagi *et al*., 2011 [29]; Elango and Roopan, 2015 [12]; Sankar *et al*., 2015) [36]. Self-cleaning nanoscale surface coatings offer sustainable alternatives to harsh cleaning chemicals (Elango and Roopan, 2015) [12], while iron-based nanoparticles (Fe NPs) are especially effective for water disinfection and remediation of heavy-metal-contaminated soils (Wang *et al*., 2014) [48].

8.3 Agriculture

Green nanotechnology is reshaping agriculture by providing environmentally benign alternatives to conventional agrochemicals. Nanoparticle-based fertilisers can increase crop yield while promoting soil health, and nanoparticles are also being explored as sustainable alternatives to chemical pesticides for plant-disease management (Kottegoda *et al*., 2011 [24]; Singh *et al*., 2015) [39]. Nano-enabled delivery systems further improve the precision and efficacy of fertiliser and pest-control application, reducing waste and environmental contamination.

8.4 Energy

In the energy sector, biogenic magnetite (Fe_3O_4) and greigite (Fe_3S_4) nanoparticles synthesised from bacteria and diatoms have been applied in solar-energy harvesting and as ion-insertion materials for batteries (Joerger *et al*., 1999) [20], while green-synthesized nanoscale catalysts enhance the efficiency of industrial chemical reactions, reducing waste generation (Nasrollahzadeh *et al*., 2015) [28].

8.5 Materials Science and Textiles

Green nanotechnology has enabled functional textiles with enhanced strain resistance, antimicrobial activity, and UV protection, extending product lifespan and reducing reliance on harsh cleaning agents (Elango and Roopan, 2015) [12].

8.6 Food Industry

In food science, nanomaterials with antimicrobial and barrier properties are being used to extend shelf life, prevent spoilage, and enhance food safety (Paul *et al*., 2023) [31].

Table 9: Sector-wise summary of green nanotechnology applications

Sector	Representative applications
Medicine & diagnostics	Antimicrobial, antifungal, and antiparasitic agents; drug delivery; diagnostic imaging
Environment	Water and wastewater treatment; heavy-metal remediation; self-cleaning coatings
Agriculture	Precision fertilisers; nano-pesticides; nano-enabled delivery systems
Energy	Solar-energy harvesting; battery electrode/ion-insertion materials; catalysis
Materials & textiles	Antimicrobial, UV-protective, strain-resistant functional fabrics
Food industry	Antimicrobial packaging; shelf-life extension; spoilage prevention

9. Challenges in Green Nanotechnology

9.1 Technical and Mechanistic Challenges

Despite substantial progress, several challenges continue to constrain the field. Control over the size, shape, and morphology of green-synthesized nanoparticles remains limited relative to well-optimised chemical routes, largely because natural extracts are chemically complex and compositionally variable differing with plant species, tissue, geographic origin, season of collection, and extraction protocol, so that the same nominal method can yield batches of differing size and polydispersity. This variability directly affects the reproducibility that regulatory and industrial applications demand. The biochemical mechanisms underlying biogenic nanoparticle formation are also still incompletely understood at the molecular level: the precise phytochemical(s) responsible for reduction versus capping are rarely identified with certainty, and reaction pathways are usually inferred indirectly from FTIR and UV-Vis data rather than resolved mechanistically. This knowledge gap could be narrowed through closer collaboration between experimental researchers and computational/theoretical groups capable of developing predictive, mechanism-based models of nucleation and growth. Scaling green synthesis from laboratory to industrial production presents a further hurdle: while laboratory-scale protocols (typically millilitre to litre scale) have repeatedly demonstrated feasibility, translating these into consistent, high-throughput, cost-effective production at pilot or industrial scale remains difficult, owing to challenges in maintaining uniform mixing, temperature control, and extract quality at larger reactor volumes.

9.2 Toxicological and Regulatory Considerations

Systematic studies of the toxicity and long-term environmental fate of biosynthesized nanoparticles remain comparatively limited relative to the volume of synthesis-focused literature, and more comprehensive nanotoxicological investigation is needed to ensure their safety relative to conventionally synthesized nanoparticles. Key concerns include potential routes of human exposure (dermal contact, inhalation, and ingestion, particularly relevant to agricultural and food-packaging applications), and the possibility that nanoparticles may cross biological barriers more readily than their bulk counterparts because of their small size and high surface-area-to-volume ratio. *In vitro* cytotoxicity is commonly assessed using assays such as MTT (cell viability) and LDH (membrane integrity) alongside markers of oxidative stress, since reactive-oxygen-species generation is both the basis of the antimicrobial activity exploited in Section 8.1 and a potential mechanism of unwanted toxicity to non-target cells; the same mechanism can therefore be beneficial or harmful depending on dose and target specificity. A further complication is that standard toxicological dose-metrics developed for bulk chemicals (mass per unit body weight) may not adequately capture nanoparticle toxicity, which is often more closely related to particle number, surface area, or surface reactivity a mismatch that complicates comparison across studies and slows the development of clear regulatory thresholds. Existing regulatory frameworks for nanomaterials (for example, OECD test guidelines for manufactured nanomaterials and region-specific frameworks such as the EU's REACH regulation) are still evolving, and biosynthesized nanoparticles whose surface chemistry depends on the specific biological source used, add an additional layer of complexity that current guidance does not yet fully address. Establishing standardised, source-traceable characterization and toxicity-testing protocols will be essential for the safe commercial deployment of green-synthesized nanoparticles.

10. Future Prospects

The application of green-synthesized nanoparticles in agriculture is an emerging area of substantial promise. Recent studies have demonstrated their potential to enhance plant growth and nutrient mobilisation for example, fungal-derived zinc oxide (ZnO) nanoparticles have been shown to mobilise phosphorus in mung bean, while biosynthesized ZnO and TiO_2 nanoparticles have produced encouraging physiological responses in tomato and mung bean. Such studies remain comparatively rare, and expanding research in this direction could unlock new opportunities for nano-enabled fertilisers and pest control within sustainable agricultural systems. Looking ahead, priority research directions include: (i) elucidating the biochemical mechanisms of biogenic nanoparticle formation through combined experimental and computational approaches; (ii) developing standardised protocols to improve reproducibility and batch-to-batch consistency; (iii) engineering scalable bioreactor-based production systems; (iv) conducting systematic nanotoxicology and life-cycle assessments; and (v) expanding forest- and agroforestry-derived precursor screening to identify novel, regionally available biosynthesis platforms.

11. Conclusion

The synthesis of nanoparticles using natural extracts has attracted significant attention because of its sustainable, eco-friendly, and cost-effective character. By avoiding harsh or toxic chemicals, green synthesis yields nanoparticles largely free of contaminants, a property of particular importance for biological and medical applications requiring high purity while the non-toxic nature of plant by-products simplifies waste disposal and enhances the overall environmental benefit of the process relative to conventional physicochemical routes. Green chemistry principles, emphasising benign solvents and biologically derived reducing and stabilising agents, provide a practical roadmap for reducing the environmental footprint of nanoparticle synthesis, with biogenic sources such as plants and microorganisms standing out for their simplicity, cost-effectiveness, and compatibility with eco-friendly practice. Realising the full potential of green nanotechnology will require sustained interdisciplinary effort to deepen mechanistic understanding, improve control over nanoparticle characteristics, establish rigorous safety data through toxicity studies, and overcome the scalability limitations that currently separate laboratory success from industrial application. Expanding the application of green-synthesized nanoparticles in agriculture, medicine, and environmental remediation will help chart a path toward a more sustainable, environmentally responsible future for nanotechnology.

12. Competing Interests

The authors declare that no competing interests exist.

13. Authors' Contributions

YPY conceptualized and designed the study, conducted the literature review, and prepared the original manuscript draft. GBG and GAN contributed to the literature search, data compilation, interpretation of the reviewed studies, and critically revised the manuscript. RS and DM contributed to manuscript review and editing. SS supervised the study, provided critical intellectual input, and reviewed and edited the final manuscript. All authors read and approved the final manuscript.

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