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Plant-Mediated Green Nanoparticles in Modern Drug Delivery: Advances in Synthesis, Characterization, Therapeutic Applications, and Safety Challenges

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Abstract: ***Background:*** ***With the increasing demand for biocompatible, cost-effective, and environmentally friendly nanocarriers, plant-mediated ("green") synthesis of metallic and metal-oxide nanoparticles has become a major direction in pharmaceutical research. Phytochemical synthesis uses the polyphenols, flavonoids, terpenoids, and proteins available in plant extracts as reducing and capping agents to produce nanoparticles that are less toxic and more biologically active than those produced by conventional physicochemical methods.*** ***Objective:*** ***This study aims to summarise the literature on the synthesis, characterisation, and therapeutic potential of plant-mediated nanoparticles over the past five years (2020-2025), focusing on their incorporation into current drug delivery systems.*** ***Methodology:*** ***We used PubMed, ScienceDirect, Web of Science/Scopus, SpringerLink, and Google Scholar to conduct the structured narrative review. We screened articles published from January 2020 to September 2025 using combinations of keywords, including green synthesis, characterisation, phytochemicals, drug delivery, plant-mediated nanoparticles, and nanotoxicology. We included articles only if they reported a synthesis mechanism, physicochemical characterisation, or a biomedical/toxicological outcome.*** ***Findings:*** ***Plant-extracted-synthesised silver, gold, zinc oxide and iron oxide nanoparticles show good physicochemical characteristics (around 1-100 nm), which are supported by the results of UV-Vis, FTIR, and XRD, TEM/SEM and dynamic light scattering studies show antimicrobial, anticancer, antioxidant, and targeted drug-delivery activities. However, important barriers to translation remain, including batch-to-batch variability, incomplete phytochemical characterisation, and insufficient long-term toxicity data.*** ***Conclusions:*** ***Plant-mediated nanoparticles are a potential scalable alternative for next-generation drug delivery, but future applications require standard synthesis protocols and thorough safety testing.***

Keywords: ***Green Synthesis; Plant-Mediated Nanoparticles; Phytochemicals; Drug Delivery; Nanotoxicology; Characterization***

Nomenclature:
TEM/SEM: Transmission and scanning electron microscopy
SAED: Selected-Area Electron Diffraction
XRD: X-Ray Diffraction
FTIR: Fourier-Transform Infrared
EDX/EDS: Energy-Dispersive X-Ray Spectroscopy
XPS: X-Ray Photoelectron Spectroscopy
DLS: Dynamic Light Scattering
SPR: Surface Plasmon Resonance

I. INTRODUCTION

Nanotechnology has revolutionised pharmaceutical sciences by enabling nanocarriers that improve solubility, bioavailability, targeting, and controlled drug release [1]. Within the family of nanocarriers, some, such as metallic nanoparticles (Ag, Au, ZnO, or Fe3O4/Fe2O3), have been of particular interest because of their tunable size, high surface-to-volume ratio, and multifunctional surface chemistry, offering possibilities for drug, targeting ligand, and imaging probe conjugation [1,2,3]. However, traditional synthesis methods for these nanoparticles involve energy-intensive and costly chemical reductants such as sodium borohydride or hydrazine, or physical methods such as laser ablation or sputtering, which produce toxic residues unsuitable for biomedical applications [1].

Green synthesis is a sustainable technique that uses biological systems such as bacteria, fungi, algae, and especially plants as reducing and stabilising agents [2]. It avoids aseptic microbial culture maintenance, high-temperature microbial growth, and the need for specialised microbial inoculation and multiplication. The process is fast at ambient temperature, making plant-mediated synthesis particularly appealing because of the number of phytochemicals (flavonoids, terpenoids, alkaloids, phenolic acids, and proteins)

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that can be reduced to nanoparticles, which also help cap the resultant nanoparticles, providing long-term colloidal stability without special microbial surfactants [2,4].

In addition to their environmental friendliness, plant-based nanoparticles exhibit intrinsic pharmacological activity ranging from antimicrobial and antioxidant to anti-inflammatory and anticancer activity, which is either additive or synergistic with the therapeutic agents they carry [3,4]. This dual function places them in a special position in contemporary drug delivery, where nanocarriers must be multifunctional rather than inert [3].

Despite the increasing interest in the field, there are still some problems to be addressed, such as the restrictions on reproducibility, lack of complete understanding of the mechanisms involved in phytochemical-metal interactions and variations in safety from one plant species to the other and from one extraction method to the other [2]. Regulatory frameworks for green nanomedicines have also developed more slowly than laboratory innovation. Thus, this review examines the mechanistic understanding of plant-mediated nanoparticle synthesis, the common analytical tools used for their characterisation, documented applications of these nanoparticles in drug delivery, and the toxicological and translational challenges described in the literature between 2020 and 2025.

II. METHODOLOGY

This review used a structured narrative review method. We conducted an electronic literature search on PubMed/MEDLINE, ScienceDirect, Scopus, SpringerLink, and Google Scholar for articles published from January 2020 to September 2025. The search terms were employed, and Boolean operators were used: ('green synthesis' OR 'plant-mediated synthesis' OR 'phytosynthesis') AND ('nanoparticles' OR 'silver nanoparticles' OR 'gold nanoparticles' OR 'zinc oxide nanoparticles' OR 'iron oxide nanoparticles') AND ('drug delivery' OR 'characterization' OR 'toxicity' OR 'biomedical application').

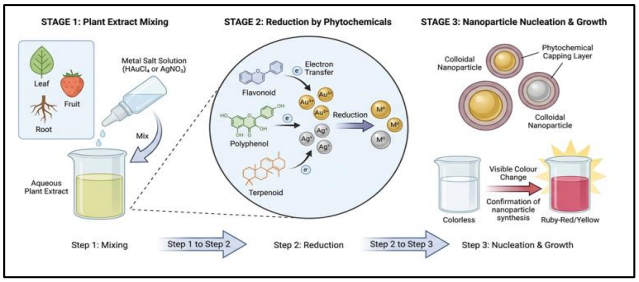
The inclusion criteria were: (a) peer-reviewed original research or review articles; (b) explicit mention of the use of extracts from plant leaves, seeds, fruits, peels, or roots as reducing/capping agents; (c) reported physicochemical characterisation data; and (d) a discussion of at least one pharmaceutical/therapeutic or toxicological endpoint. We excluded articles focused exclusively on environmental remediation, agricultural applications, or non-biomedical catalytic applications, as well as incomplete non-English publications and conference abstracts. We manually screened the reference lists of retrieved articles for additional relevant articles. For each study, we extracted the plant source, nanoparticle type, synthesis conditions, characterisation methods, reported biological/therapeutic effects, and toxicity profile. We then synthesised the extracted data narratively, and the synthesis order formed the structure of the following sections, organised under synthesis mechanisms, characterisation, therapeutic applications, and safety considerations.

III. MECHANISMS OF PLANT-MEDIATED GREEN SYNTHESIS

Plant-mediated nanoparticle synthesis follows a general bottom-up pathway of activation, growth, and termination [5,6]. During activation, a metal precursor salt (e.g., HAuCl4, AgNO3, Zn (NO3)2, FeCl3) reacts with an aqueous plant extract at ambient or slightly higher temperatures. The phytochemicals, primarily polyphenols, flavonoids, terpenoids, and reducing sugars, donate electrons to the metal ions and reduce them to a zero-valent nucleus, such as Au3+ to Au0 [5, 7]. Bioreduction mainly occurs through functional groups such as hydroxyl (-OH), carbonyl (C=O), and amine (-NH2), which FTIR spectroscopy can detect [8].

During the growth phase, atoms form larger clusters, and neighbouring phytochemicals bind to the growing nanoparticle surface; these molecules act as capping agents that prevent uncontrolled Ostwald ripening and provide steric and electrostatic stability by occupying the nanoparticle surface. The termination stage produces stable nanoparticles with thermodynamically stable characteristics such as final size, shape, and polydispersity, which are controlled by reaction parameters including extract concentration, metal-salt-to-extract ratio, pH, temperature, and reaction time [7,8]. Smaller, spherical particles tend to grow more at acidic pH, while rods, triangles, or hexagonal plates tend to grow more at alkaline pH. The incubation period is longer [7].

No single universal mechanism is observed across plant species; for instance, the relative abundance of ortho-dihydroxyl phenolics correlates with smaller, more uniform particle populations, which occurs due to better chelation of metal ions [8]. This variability is both beneficial, providing a tunable synthesis “toolbox” based on biodiversity, and a drawback, as phytochemical composition varies between plant batches from different provenances, harvested in different seasons, and extracted with different solvents [6]. Figure 1 shows the mechanism of green synthesis of metal nanoparticles using plants.



[Fig.1: Schematic Mechanism of Plant-Mediated Green Synthesis of Metal Nanoparticles (Activation, Growth, and Termination Stages)]

Sources: Adapted from mechanistic descriptions in references. [5,6].

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IV. PLANT-DERIVED NANOPARTICLE SYSTEMS AND THEIR APPLICATIONS IN DRUG DELIVERY

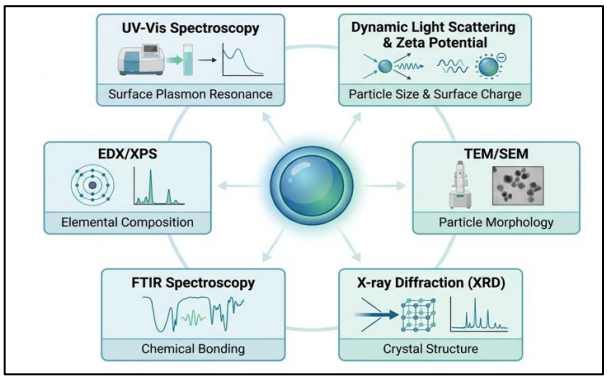
Careful physicochemical characterisation is critical to ensure nanoparticle formation and to establish the relationship between structural characteristics and biological performance. The first confirmatory technique is usually UV-visible spectroscopy, which yields the characteristic surface plasmon resonance (SPR) band, a band of collective oscillation of conduction band electrons, with a characteristic band seen around 400-450 nm for AgNPs and 520-560 nm for AuNPs [8,9]. Dynamic light scattering (DLS) provides the hydrodynamic diameter and polydispersity index, and zeta potential measurements reflect colloidal stability; values greater than ±30 mV indicate stability [9,10].

Transmission and scanning electron microscopy (TEM/SEM) can directly image morphology and size distribution and are often complemented by selected-area electron diffraction (SAED) or X-ray diffraction (XRD) to verify particle crystallinity and phase composition [10,11]. The molecules responsible for the bioactivity of the nanoparticles are linked to the chemistry of the synthesis by using Fourier-transform infrared (FTIR) spectroscopy, which identifies the specific functional groups that are adsorbed on the surface of the nanoparticle [8]. Energy-dispersive X-ray spectroscopy (EDX/EDS) and X-ray photoelectron spectroscopy (XPS) complement elemental composition and oxidation-state information, especially for metal-oxide materials like ZnO and Fe3O4 [11].

Orthogonal methods (Table I) can be used together to confirm that green nanoparticles meet the size (usually 1–100 nm), shape, and stability criteria needed for incorporation into pharmaceutical formulations, and to trace batch variability back to synthesis parameters. Table 1 provides a brief overview of common characterisation methods used for plant-mediated nanoparticles. Figure 2 gives an overview of orthogonal characterisation techniques used to validate green-synthesised nanoparticles.

Table I: Common Characterisation Techniques Applied to Plant-Mediated Nanoparticles

Technique	Parameter Assessed	Typical Output
UV-Visible spectroscopy	Optical property/surface plasmon resonance (SPR)	Confirms nanoparticle formation; SPR peak position and intensity
Dynamic Light Scattering (DLS)	Hydrodynamic size, polydispersity index (PDI)	Particle size distribution curve
Zeta potential analysis	Surface charge / colloidal stability	mV value; |>30 mV| indicates good stability
TEM / SEM	Morphology, size, shape	Micrographs and particle size histograms
X-ray Diffraction (XRD)	Crystallinity, phase composition	Diffraction pattern; crystallite size (Scherrer equation)
FTIR spectroscopy	Surface functional groups of capping phytochemicals	Absorption spectrum with functional-group assignment
EDX / EDS	Elemental composition	Elemental weight/atomic percentage spectrum
XPS	Surface chemistry, oxidation state	Binding-energy spectra



[Fig.2: Overview of Orthogonal Characterisation Techniques Used to Validate Green-Synthesised Nanoparticles]

Sources: Adapted from references [8,9].

V. PLANT-DERIVED NANOPARTICLE SYSTEMS AND THEIR APPLICATIONS IN DRUG DELIVERY

A. Silver Nanoparticles (AgNPs)

AgNPs remain among the most studied green nanomaterials, known for strong, broad-spectrum antimicrobial action due to membrane disruption, Reactive Oxygen Species (ROS) generation, and interference with microbial DNA replication [12]. After a thorough literature search, we found many plant species studied for their ability to produce AgNPs against multidrug-resistant pathogens, both Gram-positive and Gram-negative [12]. AgNPs from citrus limon zest, for example, exhibited both antioxidant and antimicrobial properties, making them ideal for wound treatment and topical formulations [13]. Beyond their direct antimicrobial effects, AgNPs have been investigated as carriers for controlled, sustained antibiotic release, capitalising on an inherent synergistic effect against bacteria when combined with the released antibiotic [14].

B. Gold Nanoparticles (AuNPs)

The outstanding biocompatibility, tunable surface plasmon resonance (SPR) and the ease of bioconjugation chemistry make AuNPs promising for diagnostic imaging and targeted drug delivery [5,15]. Plant-derived AuNPs are dose-dependent and can cause cytotoxicity in several cancer cell lines (MCF-7, HeLa, HepG2, A549) through ROS-induced mitochondrial dysfunction, caspase activation, and apoptosis [5,16]. Functionally, AuNPs have been targeted with chemotherapeutics such as doxorubicin and methotrexate to improve tumour-selective accumulation via the enhanced permeability and retention (EPR) effect, and their photothermal and photodynamic properties have enabled light-induced drug release at tumour sites [5]. Reviews on plant-based AuNP synthesis have highlighted multifunctional antimicrobial and antifungal properties, along with catalytic activity [17]. Recent studies have confirmed the antimicrobial and anticancer activities of biosynthesised AuNPs against drug-resistant microorganisms and tumour cell lines, further establishing their potential as dual-action nanomedicines for treating both infectious diseases and cancer [18].

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C. Zinc Oxide Nanoparticles (ZnO NPs)

Plant-mediated ZnO NPs have a good safety profile in normal cells and selective cytotoxicity toward cancer and microbial cells due to Zn ion and ROS release [19]. Their semiconducting and photocatalytic properties also make them suitable for stimuli-responsive drug-release systems, while their reported antidiabetic, anti-inflammatory, and wound-healing properties expand their applications beyond antimicrobials alone [19,20]. ZnO NPs can also be used to modify nanocarriers to deliver drugs in response to the acidic tumour microenvironment [20].

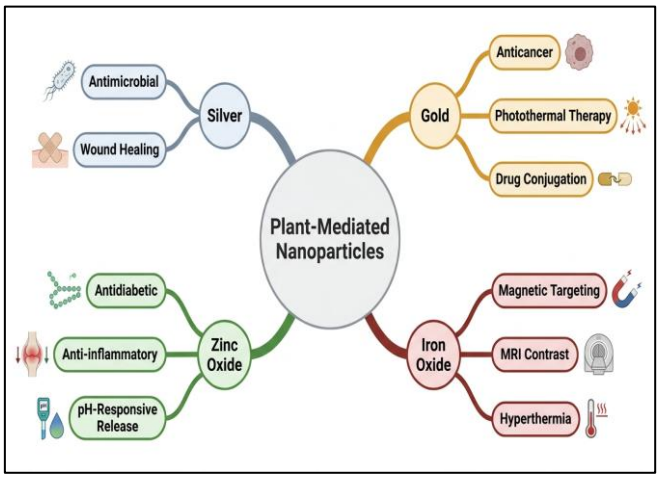
D. Iron Oxide Nanoparticles (IONPs)

Plant-mediated preparation of superparamagnetic iron oxide nanoparticles is a novel approach, as these nanoparticles offer dual imaging (MRI contrast) and therapeutic (magnetic hyperthermia and targeted drug release) capabilities [21]. Systematic review evidence suggests that plant-derived IONPs show less organ accumulation and lower oxidative toxicity than chemically synthesised IONPs, while retaining anticancer and antimicrobial bioactivity [21]. Additionally, optimised, low-cost protocols using locally available plants, such as Moringa oleifera, support scalable production in resource-limited settings [22].

In every class of nanoparticles, capping phytochemicals are often used to further stabilise the nanoparticle formulation, which helps minimise burst release and early nanoparticle aggregation in physiological fluids [23]. Table II. presents plants used for the green synthesis of nanoparticles and their reported applications in drug delivery. Figure 3 shows the Branching overview of the principal therapeutic applications of plant-mediated silver, gold, zinc oxide, and iron oxide nanoparticles in drug delivery.

Table II: Representative Plant Sources Used in Green Synthesis of Nanoparticles and Their Reported Applications Relevant to Drug Delivery

Nanoparticle	Representative Plant Source	Reported Pharmaceutical/Therapeutic Relevance	Ref.
AgNP	Citrus limon (lemon) zest	Antioxidant and antimicrobial activity; potential topical/wound-care formulations	[13]
AgNP	Rubia cordifolia (leaf)	Antibacterial and anticancer bioactivity of optimised biogenic AgNPs	[11]
AgNP	Linum usitatissimum (flaxseed)	Antibacterial and antioxidant activity	[10]
AuNP	Verbascum speciosum	Cytotoxicity against HepG2 hepatocellular carcinoma cells	[16]
AuNP	Multiple species (Camellia sinensis, Ocimum spp., others)	Anticancer activity; carrier for doxorubicin/methotrexate; cancer theranostics	[5]
AuNP	Multiple species (systematic review)	Antimicrobial, anticancer and catalytic applications	[17]
ZnO NP	Multiple plant parts (leaves, seeds, fruit)	Antimicrobial, antidiabetic, anticancer and drug-delivery applications	[19]
ZnO NP	Multiple species (review)	Antimicrobial, anti-inflammatory and biomedical applications	[20]
Fe3O4/IONP	Multiple species (systematic review)	Antimicrobial, anticancer activity; magnetically guided drug-delivery carrier	[21]
Fe3O4/IONP	Moringa oleifera	Optimised low-cost protocol for targeted drug-delivery applications	[22]



[Fig.3: Branching Overview of the Principal Therapeutic Applications of Plant-Mediated Silver, Gold, Zinc Oxide, and Iron Oxide Nanoparticles in Drug Delivery]

Sources: Adapted from references [18,19].

VI. COMPARATIVE ADVANTAGES OVER CONVENTIONAL SYNTHESIS

Compared to the chemical and physical synthesis routes, plant-mediated methods are single-step processes that operate at ambient temperatures and do not require the use of hazardous reducing agents, such as sodium borohydride and hydrazine, which would otherwise be used in the synthesis process, and significantly reduce the downstream cytotoxic residue and production cost [1]. Bare chemically synthesised nanoparticles lack the biological activity of an intrinsic phytochemical capping layer, so synthesising and capping nanoparticles in a single step is advantageous [24]. Chemical and physical methods, however, have benefits, are more reproducible, and can control particle size distribution, as the composition of plants used for extraction can vary throughout the harvest and across different geographical origins, as can the solvents used for extraction [1,24]. Table 1 summarises these considerations and suggests that plant-mediated synthesis is most suitable for biomedical applications where biocompatibility and sustainability are key factors. In contrast, applications with stringent requirements for nanoparticle purity and monodispersity might still benefit from hybrid or post-synthesis purification methods. Table III provides a comparative overview of nanoparticle synthesis, including physical, chemical, and plant-mediated (green) methods.

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Table III: Comparative Overview of Physical, Chemical, and Plant-Mediated (Green) Nanoparticle Synthesis Methods

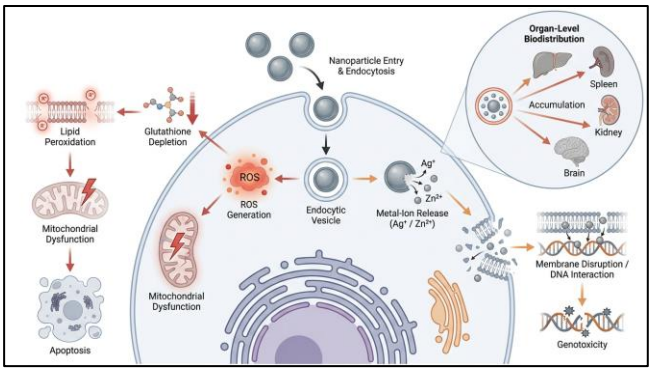
Parameter	Physical Methods	Chemical Methods	Plant-Mediated Green Synthesis
Reducing/capping agent	None (energy-driven, e.g., laser ablation)	Synthetic (e.g., NaBH4, hydrazine)	Plant phytochemicals (flavonoids, phenolics, terpenoids)
Energy requirement	High	Moderate	Low (ambient/mild heating)
Production cost	High	Moderate-high	Low
Biocompatibility/toxicity	Variable; residue-free but costly	Cytotoxic residues common	Generally improved biocompatibility
Size/shape control	Precise	Good	Moderate; extract-dependent variability
Scalability	Limited (specialized equipment)	Good	Promising but needs standardization
Environmental impact	Energy-intensive	Hazardous by-products	Low; biodegradable by-products

VII. TOXICOLOGICAL SAFETY AND REGULATORY CHALLENGES

Despite the "green" nomenclature, plant-mediated nanoparticles are not without toxicity, and thorough safety studies are still needed before clinical application [14]. The toxicological data from in vitro and in vivo studies show that the toxicity of AgNP is highly size- and dose-dependent; smaller particles (<20 nm) lead to a higher induction of oxidative stress in different tissue types, including hepatic, renal and neuronal tissue, as well as to an increased cellular uptake [14]. Similar size-related cytotoxic concentration was established for AuNPs, which can cause mitochondrial dysfunction and inflammatory responses when the concentration is not optimised [25].

Proposed toxicity mechanisms focus on two main pathways: an oxidative-stress pathway, triggered by excessive ROS generation, glutathione depletion, and lipid peroxidation, and non-oxidative mechanisms, such as direct membrane disruption, ion release (e.g., Ag+ and Zn2+), and genotoxic interaction with DNA [14,25]. Organ-level studies report preferential targeting of nanoparticles to the liver, spleen, and kidney, and, to a lesser degree, the brain, raising concerns about chronic exposure and long-term clearance kinetics [21,25].

Fortunately, comparative studies show that phytochemical capping can offer some protection for certain toxicity endpoints compared with chemically synthesised capping agents, perhaps due to lower surface reactivity and slower ion-release rates [21]. However, the toxicological literature remains somewhat divided, with studies reporting different doses, exposure durations, particle characterisation, and animal models, making cross-study comparisons and harmonisation across regulatory authorities difficult [14,25]. To date, no specific regulatory guidance exists for plant-mediated nanomedicines, and regulators typically evaluate them through general nanomaterial frameworks that do not account for the compositional complexity of phytochemical capping layers. To enable reliable risk assessment and regulatory acceptance of green nanomedicines, standardised reporting frameworks are urgently needed that include plant sourcing, extraction protocols, complete nanoparticle characterisation, and tiered in vitro/in vivo toxicity testing [14,25]. Figure 4 presents the Toxicological pathways of plant-derived nanoparticles at the cellular and organ levels.



[Fig.4: Cellular and Organ-Level Toxicological Pathways Associated with Plant-Mediated Nanoparticles]

Sources: Adapted from references [14,25]. Noga et al.

VIII. CHALLENGES AND FUTURE PERSPECTIVES

Main translational challenges include variability in uncharacterized phytochemical mixtures across batches, limited scale-up of laboratory procedures to industrial (GMP) production, and a lack of long-term pharmacokinetics and chronic toxicity data in relevant animal models [6,7]. The future directions include: (i) standardised extraction and synthesis protocols with well-defined phytochemical fingerprinting (HPLC/LC-MS); (ii) elucidating the mechanisms of specific phytoconstituent-metal interactions for rational and reproducible design; (iii) combination of green nanoparticles with stimuli-responsive polymers or ligand-targeting moieties for precision drug delivery; and (iv) harmonised regulatory guidance for biologically capped nanomedicines. Continued innovation in computational formulation optimisation and the introduction of green-chemistry metrics, such as E-factor and atom economy, can further drive the responsible scale-up of plant-made nanoparticles from bench to clinic.

IX. CONCLUSION

Green synthesis of nanoparticles using plants has evolved into a viable, eco-friendly alternative to traditional nanoparticle fabrication, characterised by intrinsic biocompatibility, multifunctional therapeutic potential, and lower environmental impact. Silver, gold, zinc oxide, and iron oxide nanoparticles prepared using various plant-based materials have shown promising antimicrobial, anticancer, and targeted drug-delivery properties, as shown by detailed spectroscopic and microscopic analyses. However, major challenges remain: improving reproducibility in the field, understanding the

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mechanisms of phytochemical bioreduction, and developing strong, standardised toxicological and regulatory frameworks. Plant-mediated nanoparticles have tremendous potential to contribute significantly to the next generation of safe and sustainable drug delivery systems, with continued interdisciplinary effort in phytochemistry, nanotechnology, and pharmaceutical sciences.

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- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate, with supporting documentation.
- **Data Access Statement and Material Availability:** The data in this article are publicly accessible.
- **Authors' Contributions:** The authorship of this article is contributed equally to all participating individuals.

REFERENCES

1. Ijaz I, Gilani E, Nazir A, Bukhari A. Detailed review on chemical, physical and green synthesis, classification, characterisations and applications of nanoparticles. Green Chem Lett Rev. 2020;13(3):223-245. DOI: 10.1080/17518253.2020.1802517
2. Jadoun S, Arif R, Jangid NK, Meena RK. Green synthesis of nanoparticles using plant extracts: a review. Environ Chem Lett. 2021;19(1):355-374. DOI: 10.1007/s10311-020- 01074-x
3. Lee KX, Shameli K, Yew YP, Teow SY, Jahangirian H, Rafiee-Moghaddam R, et al. Recent developments in the facile biosynthesis of gold nanoparticles (AuNPs) and their biomedical applications. Int J Nanomedicine. 2020; 15:275-300. DOI: 10.2147/IJN.S233789
4. Amina SJ, Guo B. A review on the synthesis and functionalization of gold nanoparticles as a drug delivery vehicle. Int J Nanomedicine. 2020; 15:9823-9857. DOI: 10.2147/IJN.S279094
5. Bharadwaj KK, Rabha B, Pati S, Sarkar T, Choudhury BK, Barman A, et al. green synthesis of gold nanoparticles using plant extracts as a beneficial prospect for cancer theranostics. Molecules. 2021;26(21):6389. DOI: 10.3390/molecules26216389
6. Singh H, Desimone MF, Pandya S, Jasani S, George N, Adnan M, et al. Revisiting the green synthesis of nanoparticles: uncovering influences of plant extracts as reducing agents for enhanced synthesis efficiency and its biomedical applications. Int J Nanomedicine. 2023; 18:4727-4750. DOI: 10.2147/IJN.S419369
7. Azad A, Zafar H, Raza F, Sulaiman M. Factors influencing the green synthesis of metallic nanoparticles using plant extracts: a comprehensive review. Pharm Fronts. 2023;5(3): e117-e131. DOI: 10.1055/s-0043-1774289
8. Zuhrotun A, Oktaviani DJ, Hasanah AN. Biosynthesis of gold and silver nanoparticles using phytochemical compounds. Molecules. 2023;28(7):3240. DOI: 10.3390/molecules28073240
9. Eker F, Akdaşçi E, Duman H, Bechelany M, Karav S. Green synthesis of silver nanoparticles using plant extracts: a comprehensive review of physicochemical properties and multifunctional applications. Int J Mol Sci. 2025;26(13):6222. DOI: 10.3390/ijms26136222
10. Alzubaidi AK, Al-Kaabi WJ, Ali AA, Albukhaty S, Al-Karagoly H, Sulaiman GM, et al. Green synthesis and characterisation of silver nanoparticles using flaxseed extract and evaluation of their antibacterial and antioxidant activities. Appl Sci. 2023;13(4):2182. DOI: 10.3390/app13042182
11. Chandraker SK, Lal M, Khanam F, Dhruve P, Singh RP, Shukla R. Therapeutic potential of biogenic and optimised silver nanoparticles using Rubia cordifolia L. leaf extract. Sci Rep. 2022;12(1):8831. DOI: 10.1038/s41598-022-12878-y
12. Vanlalveni C, Lallianrawna S, Biswas A, Selvaraj M, Changmai B, Rokhum SL. Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: a review of recent literature. RSC Adv. 2021;11(5):2804-2837. DOI: 10.1039/D0RA09941D
13. Khane Y, Benouis K, Albukhaty S, Sulaiman GM, Abomughaid MM, Al Ali A, et al. Green synthesis of silver nanoparticles using aqueous Citrus limon zest extract: characterisation and evaluation of their antioxidant and antimicrobial properties. Nanomaterials. 2022;12(12):2013. DOI: 10.3390/nano12122013
14. Noga M, Milan J, Frydrych A, Jurowski K. Toxicological aspects, safety assessment, and green toxicology of silver nanoparticles (AgNPs)-critical review: state of the art. Int J Mol Sci. 2023;24(6):5133. DOI: 10.3390/ijms24065133
15. Mobaraki F, Momeni M, Taghavizadeh Yazdi ME, Meshkat Z, Silanian Toosi M, Hosseini SM. Plant-derived synthesis and characterisation of gold nanoparticles: investigation of their antioxidant and anticancer activity against human testicular embryonic carcinoma stem cells. Process Biochem. 2021; 111:167-177. DOI: 10.1016/j.procbio.2021.09.010
16. Mousavi-Kouhi SM, Beyk-Khormizi A, Mohammadzadeh V, Ashna M, Es-haghi A, Mashreghi M, et al. Biological synthesis and characterisation of gold nanoparticles using Verbascum speciosum Schrad. and cytotoxicity properties toward the HepG2 cancer cell line. Res Chem Intermed. 2022;48(1):167-178. DOI: 10.1007/s11164-021-04600-w
17. Dash SS, Sen IK, Dash SK. A review on the plant extract-mediated green syntheses of gold nanoparticles and their antimicrobial, anticancer, and catalytic applications. Int Nano Lett. 2022;12(1):47-66. DOI: 10.1007/s40089-021-00358-6
18. Huq MA, Rana MR, Samad A, Rahman MS, Rahman MM, Ashrafudoulla M, et al. Green synthesis, characterisation, and potential antibacterial and anticancer applications of gold nanoparticles: current status and prospects. Biomedicines. 2025;13(5):1184. DOI: 10.3390/biomedicines13051184
19. Murali M, Kalegowda N, Gowtham HG, Ansari MA, Alomary MN, Alghamdi S, et al. Plant-mediated zinc oxide nanoparticles: advances in the new millennium towards understanding their therapeutic role in biomedical applications. Pharmaceutics. 2021;13(10):1662. DOI: 10.3390/pharmaceutics13101662
20. Alhujaily M, Albukhaty S, Yusuf M, Mohammed MKA, Sulaiman GM, Al-Karagoly H,et al. Recent advances in plant-mediated zinc oxide nanoparticles with their significant biomedical properties. Bioengineering. 2022;9(10):541. DOI: 10.3390/bioengineering9100541
21. Hamdy NM, Boseila AA, Ramadan A, Basalious EB. Iron oxide nanoparticles-plant insignia synthesis with favourable biomedical activities and less toxicity, in the "era of the-green": a systematic review. Pharmaceutics. 2022;14(4):844. DOI: 10.3390/pharmaceutics14040844
22. Kiwumulo HF, Muwonge H, Ibingira C, Lubwama M, Kirabira JB, Ssekitoleko RT. Green synthesis and characterisation of iron-oxide nanoparticles using Moringa oleifera: a potential protocol for use in low- and middle-income countries. BMC Res Notes. 2022;15(1):149. DOI: 10.1186/s13104-022-06039-7
23. Zhou F, Peterson T, Fan Z, Wang S. The commonly used stabilisers for phytochemical- based nanoparticles: stabilisation effects, mechanisms, and applications. Nutrients. 2023;15(18):3881. DOI: 10.3390/nu15183881
24. Rajakumar G, Sudha PN, Thiruvengadam M. Synthesis, bioactivity evaluation and application of plant-based nanoparticles. Molecules. 2023;28(12):4783. DOI: 10.3390/molecules28124783
25. Niżnik Ł, Noga M, Kobylarz D, Frydrych A, Krośniak A, Kapka-Skrzypczak L, et al. Gold nanoparticles (AuNPs): toxicity, safety and green synthesis: a critical review. Int J Mol Sci. 2024;25(7):4057. DOI: 10.3390/ijms25074057

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