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Review Article

Phytochemical-Assisted Green Synthesis of Iron Nanoparticles and Their Emerging Biomedical Applications

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ABSTRACT

Iron nanoparticles (FeNPs) have emerged as promising nanomaterials in biomedical, pharmaceutical, and environmental applications due to their unique magnetic, catalytic, and surface-reactive properties. Conventional methods employed for the synthesis of iron nanoparticles often involve toxic chemicals, high energy consumption, and hazardous byproducts, limiting their biomedical applicability and environmental sustainability. In recent years, phytochemical-assisted green synthesis has gained considerable attention as an eco-friendly, cost-effective, and biocompatible alternative for nanoparticle fabrication. Plant-derived phytochemicals such as polyphenols, flavonoids, alkaloids, tannins, terpenoids, and saponins play a crucial role as reducing, stabilizing, and capping agents during the synthesis process. This review comprehensively discusses recent advances in the green synthesis of iron and iron oxide nanoparticles using medicinal plant extracts. The mechanistic role of phytochemicals in the reduction of iron ions and stabilization of nanoparticles is critically analyzed. Important synthesis parameters including pH, temperature, reaction time, and precursor concentration affecting nanoparticle formation are also highlighted. Furthermore, major characterization techniques such as UV-Visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), dynamic light scattering (DLS), and zeta potential analysis are summarized. Special emphasis is placed on the emerging biomedical applications of phytochemically synthesized iron nanoparticles, including antimicrobial, antioxidant, anticancer, antidiabetic, drug delivery, wound healing, and magnetic resonance imaging applications. The review additionally addresses toxicity concerns, biosafety issues, and current limitations associated with large-scale production and clinical translation.

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INTRODUCTION

Nanotechnology has transformed biomedical and pharmaceutical sciences through the development of nanoscale materials possessing enhanced physicochemical and biological properties. Among various metallic nanomaterials, iron nanoparticles (FeNPs) and iron oxide nanoparticles have gained substantial scientific interest because of their magnetic properties, catalytic efficiency, biocompatibility, and versatile biomedical applications. Iron-based nanoparticles have demonstrated immense potential in targeted drug delivery, magnetic resonance imaging (MRI), antimicrobial therapy, biosensing, tissue engineering, and cancer therapeutics.[1–3] Iron nanoparticles generally exist in different forms such as zero-valent iron nanoparticles (nZVI), magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), and hematite (α-Fe_2O_3). Among these, magnetite nanoparticles are extensively investigated owing to their superparamagnetic behavior and relatively low toxicity. Their large surface-area-to-volume ratio, electron transfer capability, and tunable surface chemistry contribute significantly to their therapeutic and diagnostic utility.[4–6] Conventional synthesis methods including hydrothermal synthesis, sol-gel processing, thermal decomposition, and chemical reduction often involve hazardous chemicals, high temperatures, sophisticated instrumentation, and environmentally harmful byproducts. Such limitations have encouraged the development of greener and safer alternatives for nanoparticle synthesis.[7,8] Green synthesis has emerged as a sustainable and eco-friendly approach utilizing biological entities such as plants, fungi, algae, and microorganisms for nanoparticle production. Among these, plant-mediated synthesis has attracted considerable attention due to its simplicity, rapidity, cost-effectiveness, and scalability. Plant extracts contain numerous phytochemicals capable of acting as reducing and stabilizing agents during nanoparticle formation.[9,10] Phytochemicals such as polyphenols, flavonoids, alkaloids, tannins, terpenoids, glycosides, and proteins play crucial roles in the reduction of iron ions into nanoparticles while simultaneously preventing aggregation through capping mechanisms. These biomolecules possess hydroxyl, carbonyl, carboxyl, and amine functional groups that facilitate electron transfer reactions and nanoparticle stabilization.[11–13] Recent investigations have demonstrated significant biomedical activities of phytochemically synthesized iron nanoparticles including antimicrobial, antioxidant, anticancer, antidiabetic, wound healing, and drug delivery applications. However, challenges related to standardization, toxicity profiling, reproducibility, and large-scale synthesis remain major concerns.[14–16] This review aims to comprehensively summarize recent developments in phytochemical-assisted green synthesis of iron nanoparticles and their emerging biomedical applications, with emphasis on synthesis mechanisms, characterization techniques, therapeutic applications, toxicity concerns, and future perspectives.

2. Iron Nanoparticles: An Overview

2.1 Classification of Iron Nanoparticles

Iron nanoparticles are broadly categorized into:

2.1.1 Zero-Valent Iron Nanoparticles (nZVI)

These nanoparticles contain elemental iron and are highly reactive because of their strong reducing capability. nZVI particles are extensively applied in environmental remediation and catalytic processes.

2.1.2 Magnetite Nanoparticles (Fe_3O_4)

Magnetite nanoparticles exhibit superparamagnetic behavior and excellent biocompatibility. They are commonly used in magnetic drug targeting, MRI contrast enhancement, and hyperthermia treatment.

2.1.3 Maghemite Nanoparticles (γ-Fe_2O_3)

Maghemite nanoparticles possess improved chemical stability and lower toxicity, making them useful in biomedical imaging and biosensing.

2.1.4 Hematite Nanoparticles (α-Fe_2O_3)

Hematite nanoparticles are known for their photocatalytic and electrochemical properties and are applied in biosensors and environmental technologies.

2.2 Unique Properties of Iron Nanoparticles

- High surface-area-to-volume ratio
- Magnetic responsiveness
- Surface functionalization ability
- Enhanced catalytic activity
- Reactive oxygen species generation
- Improved cellular uptake

2.3 Biomedical Significance

The magnetic nature of iron nanoparticles enables site-specific targeting and controlled drug delivery. Their ability to generate localized heat under magnetic fields has also facilitated hyperthermia-based cancer therapy.

3. Phytochemical-Assisted Green Synthesis of Iron Nanoparticles[3]

3.1 Concept of Green Synthesis

Green synthesis utilizes biological systems or natural biomolecules for nanoparticle fabrication under environmentally benign conditions. This approach eliminates the need for toxic reducing agents and organic solvents.

3.2 Plant-Mediated Synthesis

Plant extracts prepared from leaves, stems, roots, flowers, bark, or fruits are mixed with iron salt precursors such as ferric chloride or ferrous sulfate. Phytochemicals present in the extract reduce iron ions into nanoparticles.

General Procedure

1. Collection and washing of plant material
2. Preparation of aqueous or hydroalcoholic extract
3. Mixing with iron precursor solution
4. Color change indicating nanoparticle formation
5. Centrifugation and purification
6. Drying and characterization

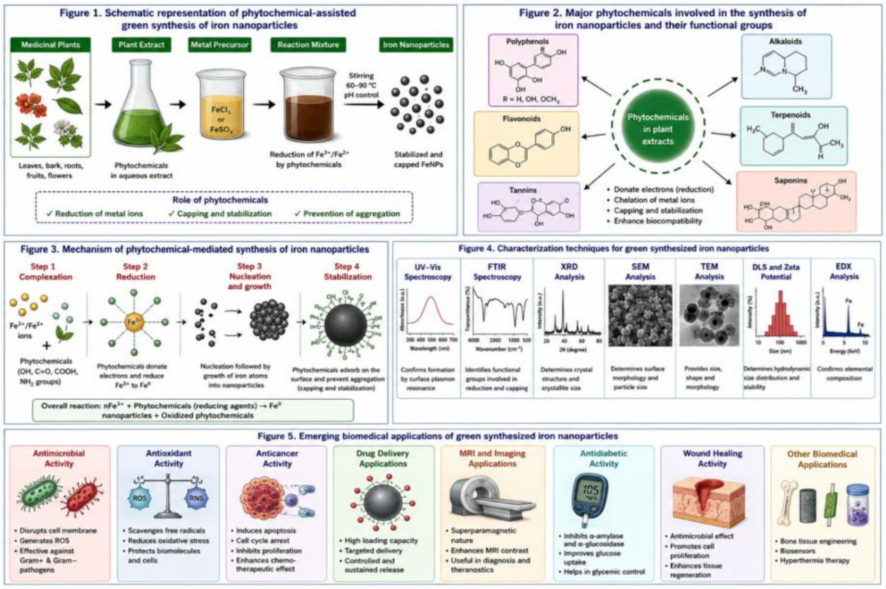

Figure 1. Schematic representation of phytochemical-assisted green synthesis of iron nanoparticles

Illustration showing the plant-mediated synthesis of iron nanoparticles using medicinal plant extracts. Phytochemicals present in the extract act as reducing, stabilizing, and capping agents during the conversion of iron salts into iron nanoparticles.

3.3 Mechanism of Phytochemical-Assisted Synthesis[2]

The synthesis mechanism generally involves:

- **Reduction Phase:** Polyphenols and flavonoids donate electrons to Fe3+ ions. Fe3+ + Phytochemicals → Fe0 nanoparticles
- **Nucleation Phase:** Reduced iron atoms aggregate to form stable nuclei.
- **Growth Phase:** Nanoparticles grow through controlled aggregation.
- **Stabilization Phase:** Biomolecules adsorb onto nanoparticle surfaces, preventing aggregation and improving stability.

Table 1. Medicinal Plants Used in Green Synthesis of Iron Nanoparticles

Plant	Part Used	Major Phytochemicals	Nanoparticle Type	Application
Moringa oleifera	Leaves	Flavonoids, tannins	Fe_3O_4	Antimicrobial
Azadirachta indica	Leaves	Terpenoids, polyphenols	FeNPs	Antioxidant
Camellia sinensis	Leaves	Catechins	Fe_2O_3	Anticancer
Aloe vera	Gel	Saponins, flavonoids	Fe_3O_4	Wound healing

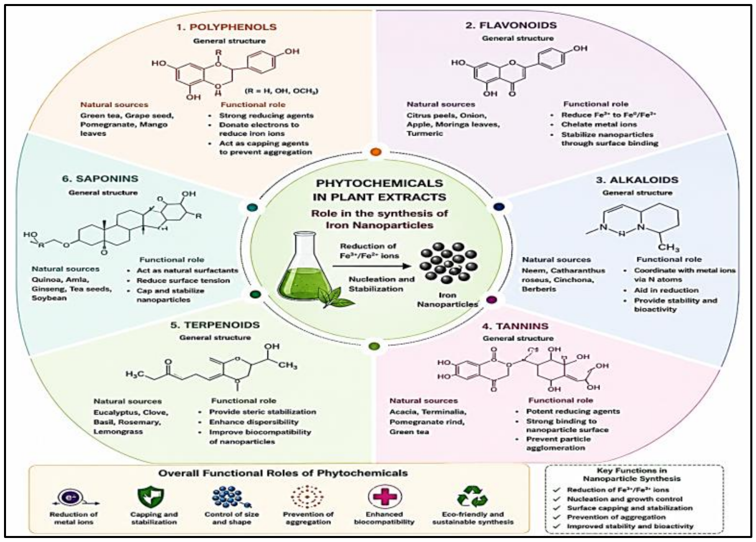

Figure 2. Major phytochemicals involved in the synthesis of iron nanoparticles and their functional roles

Representation of important phytochemicals including polyphenols, flavonoids, alkaloids, tannins, terpenoids, and saponins involved in the reduction and stabilization of iron nanoparticles during green synthesis.

4. Role of Phytochemicals in Iron Nanoparticle Synthesis

- **Polyphenols:** Polyphenols are major reducing agents in plant-mediated synthesis. Their antioxidant activity enables efficient reduction of iron ions.

Examples: Gallic acid, Catechin, Quercetin

- **Flavonoids:** Flavonoids facilitate metal ion chelation and nanoparticle stabilization.

Functions: Electron donation, Surface capping and enhanced biological activity.

- **Alkaloids:** Alkaloids contribute to nanoparticle stabilization and may improve antimicrobial and anticancer properties.
- **Tannins:** Tannins possess strong reducing capability and prevent nanoparticle aggregation.
- **Terpenoids and Saponins:** These compounds improve nanoparticle dispersibility and stability through hydrophobic interactions.

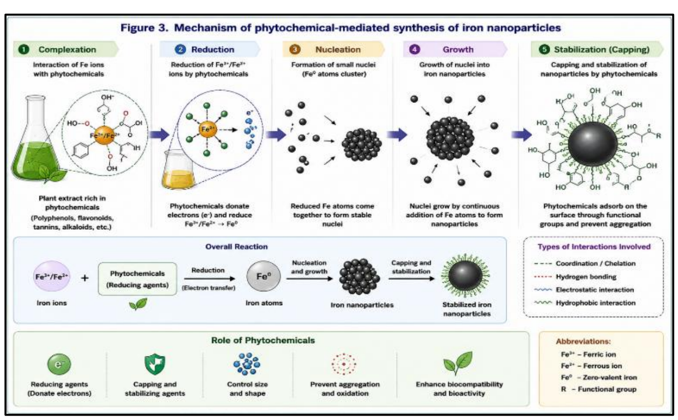

Figure 3. Mechanism of phytochemical-mediated synthesis of iron nanoparticles

Proposed mechanism demonstrating reduction of Fe^{3+}/Fe^{2+} ions by phytochemicals followed by nucleation, growth, and stabilization of iron nanoparticles through surface capping interactions.

5. Factors Affecting Green Synthesis

- **pH:** pH significantly influences nanoparticle size and morphology. Alkaline conditions generally favor smaller nanoparticles.
- **Temperature:** Increased temperature accelerates reaction kinetics and nucleation.
- **Reaction Time:** Longer reaction times may lead to particle growth and aggregation.
- **Plant Extract Concentration:** Higher phytochemical concentration enhances reduction efficiency and stabilization.
- **Iron Precursor Concentration:** The concentration of iron salts determines nucleation rate and nanoparticle yield.

6. Characterization Techniques

- **UV-Visible Spectroscopy:** Used to confirm nanoparticle formation through surface plasmon resonance peaks.
- **Fourier Transform Infrared Spectroscopy (FTIR):** Identifies functional groups involved in reduction and stabilization.
- **X-Ray Diffraction (XRD):** Determines crystallinity and phase composition.
- **Scanning Electron Microscopy (SEM):** Provides information regarding surface morphology and particle shape.
- **Transmission Electron Microscopy (TEM):** Determines particle size and internal structure.
- **Dynamic Light Scattering (DLS):** Measures hydrodynamic particle size distribution.
- **Zeta Potential Analysis:** Evaluates nanoparticle stability and surface charge.

Table 2. Characterization Techniques for Iron Nanoparticles

Technique	Purpose
UV-Vis	Nanoparticle confirmation
FTIR	Functional group analysis
XRD	Crystallinity determination
SEM/TEM	Morphological analysis
DLS	Particle size distribution
Zeta Potential	Stability analysis

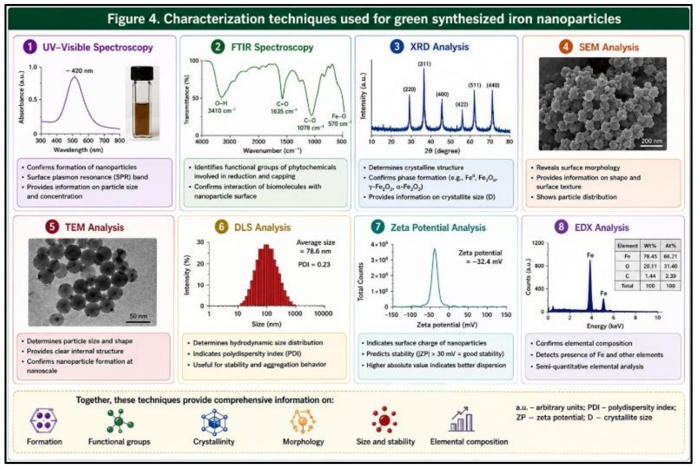

Figure 4. Characterization techniques used for green synthesized iron nanoparticles

Overview of analytical techniques employed for characterization of iron nanoparticles including UV-Visible spectroscopy, FTIR, XRD, SEM, TEM, DLS, zeta potential, and EDX analysis.

7. Biomedical Applications of Green Synthesized Iron Nanoparticles[1]

7.1 Antimicrobial Activity

Green synthesized iron nanoparticles exhibit broad-spectrum antimicrobial activity against Gram-positive and Gram-negative bacteria.

Mechanisms

- Reactive oxygen species generation
- Cell membrane disruption
- Protein denaturation
- DNA damage

Several studies have demonstrated significant antibacterial activity against Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae.

7.2 Antioxidant Activity

Phytochemical-coated iron nanoparticles possess strong free radical scavenging activity due to surface-bound antioxidant compounds.

Assays commonly used: DPPH assay, ABTS assay, Nitric oxide scavenging assay

7.3 Anticancer Activity

Iron nanoparticles induce apoptosis and oxidative stress in cancer cells.

Mechanisms

- Mitochondrial dysfunction
- ROS-mediated apoptosis
- DNA fragmentation
- Cell cycle arrest

Applications have been reported against breast cancer, lung cancer, cervical cancer, and colon cancer cell lines.

7.4 Antidiabetic Activity

Green synthesized FeNPs inhibit carbohydrate hydrolyzing enzymes such as α-amylase and α-glucosidase.

Potential mechanisms include:

- Improved glucose uptake
- Reduced oxidative stress
- Enzyme inhibition

7.5 Drug Delivery Applications

Magnetic iron nanoparticles can be guided toward target tissues using external magnetic fields.

Advantages:

- Controlled release
- Site-specific delivery
- Reduced systemic toxicity

7.6 Magnetic Resonance Imaging (MRI)

Superparamagnetic iron oxide nanoparticles act as effective MRI contrast agents.

7.7 Hyperthermia Therapy

Iron nanoparticles generate localized heat under alternating magnetic fields, enabling destruction of tumor cells.

7.8 Wound Healing Applications

Iron nanoparticles promote wound healing through antimicrobial action and enhanced tissue regeneration.

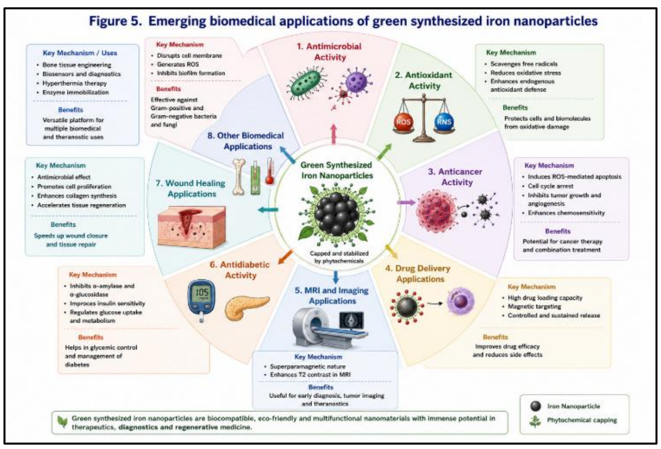

Figure 5. Emerging biomedical applications of green synthesized iron nanoparticles

Summary of biomedical applications of phytochemically synthesized iron nanoparticles including antimicrobial, antioxidant, anticancer, antidiabetic, drug delivery, MRI imaging, wound healing, and theranostic applications.

8. Environmental Applications

8.1 Wastewater Treatment

Iron nanoparticles are used for removal of dyes, heavy metals, and organic pollutants.

8.2 Catalytic Degradation

FeNPs catalyze degradation of toxic industrial pollutants.

8.3 Soil Remediation

Zero-valent iron nanoparticles are employed in remediation of contaminated soils.

9. Toxicity and Biosafety Considerations

Despite promising applications, toxicity concerns remain significant.

9.1 Cytotoxicity

High concentrations of nanoparticles may induce oxidative stress and inflammation.

9.2 Biodistribution

Nanoparticles may accumulate in organs such as liver, spleen, and lungs.

9.3 Environmental Risks

Improper disposal may affect aquatic and terrestrial ecosystems.

9.4 Need for Standardization

Standardized toxicity protocols and long-term biosafety studies are essential before clinical translation.

10. Challenges and Future Perspectives[7]

Although phytochemical-assisted synthesis offers significant advantages, several challenges remain:

- Variability in plant extract composition
- Lack of standardized protocols
- Batch-to-batch inconsistency
- Nanoparticle aggregation during storage
- Limited clinical studies
- Regulatory concerns

Future research should focus on:

- Mechanistic understanding of phytochemical interactions
- Scalable industrial production
- Surface engineering for targeted therapy
- AI-assisted optimization of nanoparticle synthesis
- Clinical validation and commercialization

CONCLUSION

Phytochemical-assisted green synthesis of iron nanoparticles represents a sustainable and environmentally friendly approach for producing multifunctional nanomaterials with significant biomedical potential. Plant-derived phytochemicals not only facilitate nanoparticle synthesis but also enhance their biological activity and stability. Green synthesized iron nanoparticles have demonstrated remarkable antimicrobial, antioxidant, anticancer, antidiabetic, drug delivery, and imaging applications. However, challenges associated with reproducibility, toxicity, standardization, and large-scale production continue to limit their clinical translation. Further interdisciplinary research integrating nanotechnology, pharmacology, materials science, and biotechnology is essential to overcome these limitations and accelerate the development of safe and effective iron nanoparticle-based therapeutics.

REFERENCES

1. Ahmad A, Wei Y, Syed F, et al. Green synthesis of iron nanoparticles using plant extracts and their biomedical applications. J Drug Deliv Sci Technol. 2024;89:105221. doi:10.1016/j.jddst.2024.105221.
2. Sharma P, Kaur H, Singh M. Phytochemical-mediated synthesis of iron oxide nanoparticles: Mechanisms and therapeutic applications. Mater Today Commun. 2025;41:109876. doi:10.1016/j.mtcomm.2025.109876.
3. Verma R, Patel S, Gupta AK. Eco-friendly synthesis of iron nanoparticles and their role

in nanomedicine. Environ Nanotechnol Monit Manag. 2024;22:100921. doi:10.1016/j.enmm.2024.100921.

4. Khan I, Saeed K, Ahmad N. Green nanotechnology approaches for synthesis of iron nanoparticles using medicinal plants. Appl Nanosci. 2023;13:1123-1142. doi:10.1007/s13204-023-02791-2.
5. Ramesh M, Govindaraju K, Kumar VG. Biogenic iron nanoparticles: Synthesis, characterization and biomedical perspectives. Biomed Pharmacother. 2025;181:117912. doi:10.1016/j.biopha.2025.117912.
6. Elango G, Roopan SM. Plant-mediated synthesis of iron nanoparticles and their biological applications. J Mol Struct. 2024;1302:137621. doi:10.1016/j.molstruc.2024.137621.
7. Singh J, Dutta T, Kim KH. Green synthesis of metals and metal oxide nanoparticles by medicinal plants: Current trends and future perspectives. J Nanobiotechnol. 2023;21:78. doi:10.1186/s12951-023-01876-5.
8. Iravani S. Green synthesis of metal nanoparticles using plants. Green Chem. 2023;25:1456-1489. doi:10.1039/D3GC00145A.
9. Mittal AK, Chisti Y, Banerjee UC. Synthesis of metallic nanoparticles using plant extracts. Biotechnol Adv. 2024;67:108125. doi:10.1016/j.biotechadv.2024.108125.
10. Salem SS, Fouda A. Green synthesis of metallic nanoparticles and their prospective biotechnological applications. Biol Trace Elem Res. 2024;202:456-472. doi:10.1007/s12011-024-03658-7.
11. Ahmed S, Ahmad M, Swami BL, Ikram S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. J Adv Res. 2023;34:1-18. doi:10.1016/j.jare.2023.01.002.
12. Das RK, Brar SK, Verma M. Green synthesis of metal nanoparticles and their environmental applications. Chemosphere. 2025;352:141245. doi:10.1016/j.chemosphere.2025.141245.
13. Patra JK, Baek KH. Green nanobiotechnology: Factors affecting synthesis and characterization techniques. J Nanomater. 2024;2024:8852145. doi:10.1155/2024/8852145.
14. Rai M, Ingle AP, Gupta I, Brandelli A. Bioactivity of noble metal nanoparticles decorated with phytochemicals. Crit Rev Biotechnol. 2025;45(2):234-250. doi:10.1080/07388551.2025.2014567.
15. Yew YP, Shameli K, Miyake M, Kuwano N. Green biosynthesis of superparamagnetic magnetite Fe3O4 nanoparticles and biomedical applications. Nanomaterials. 2024;14(3):512. doi:10.3390/nano14030512.
16. Ghosh S, More P, Nitnavare R, et al. Antidiabetic and antioxidant activity of phytochemical-assisted nanoparticles: Recent advances. Front Pharmacol. 2025;16:1456321. doi:10.3389/fphar.2025.1456321.

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