

Green Biosynthesis of Metal and Metal Oxide Nanoparticles Using Plant Extracts and Their Multifunctional Biomedical and Environmental Applications

Jelang Jelku D. Sangma^{1,2,3} 

¹Department of Food Science and Nutrition, University of Agricultural Sciences, GKVK, Bangalore, Karnataka, 560065, India

²AICRP-WIA, ICAR (CIWA), Bhubaneswar, College of Community Science, Central Agricultural University, Tura, Meghalaya - 794005, India

³Eudoxia Research University, 256 Chapman Road STE 105-4, New Castle, USA

Corresponding author: **Jelang Jelku D. Sangma** | E-mail: jelang.jelku3@gmail.com

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Abstract

Green synthesis of metal and metal oxide nanoparticles using plant extracts has emerged as an eco-friendly, cost-effective, and sustainable alternative to conventional physical and chemical methods. Plant-mediated synthesis utilizes bioactive phytochemicals such as flavonoids, phenolics, alkaloids, and proteins as reducing, stabilizing, and capping agents. This review highlights recent advances in the green synthesis of nanoparticles, focusing on synthesis mechanisms, characterization techniques, and factors influencing nanoparticle formation. Additionally, the multifunctional applications of these nanoparticles in biomedical fields—including antimicrobial, anticancer, antioxidant, and drug delivery systems—are discussed. Environmental applications such as wastewater treatment, pollutant degradation, and heavy metal removal are also explored. Despite significant progress, challenges related to large-scale production, stability, and toxicity remain. Future perspectives emphasize the need for standardization, mechanistic insights, and translational research for industrial and clinical applications.

Keywords: Green synthesis, nanoparticles, plant extracts, metal oxide nanoparticles, biomedical applications, environmental remediation.

1. Introduction

Nanotechnology has emerged as one of the most transformative fields in modern science, offering innovative solutions across disciplines such as medicine, agriculture, environmental science, and materials engineering. At the core of this field lies the development and application of nanoparticles, which typically range in size from 1 to 100 nanometers. Due to their nanoscale dimensions, these materials exhibit unique physicochemical properties, including high surface area-to-volume ratio, enhanced reactivity, optical tunability, and improved catalytic efficiency [1-2]. These distinctive characteristics make nanoparticles highly valuable for a wide range of industrial, biomedical, and environmental applications. Conventionally, nanoparticles are synthesized using physical and chemical methods such as laser ablation, chemical reduction, sol-gel processing, and thermal decomposition. While these approaches are effective in producing nanoparticles with controlled size and morphology, they often involve the use of toxic chemicals, high energy inputs, and expensive instrumentation.

Additionally, these methods can generate hazardous byproducts that pose risks to both human health and the environment [3]. As global awareness of sustainability and environmental safety increases, there is a growing demand for greener and more sustainable alternatives to traditional nanoparticle synthesis techniques. Green synthesis of nanoparticles has therefore gained significant attention as an eco-friendly and cost-effective approach. This method aligns with the principles of green chemistry, emphasizing the reduction or elimination of hazardous substances in the design and production of chemical products. Among various biological approaches, plant-mediated synthesis has emerged as a particularly promising strategy due to its simplicity, scalability, and efficiency. Unlike microbial synthesis, which requires strict aseptic conditions and longer processing times, plant extract-based synthesis is rapid, straightforward, and does not require complex culture maintenance. Plant extracts are rich in a diverse array of bioactive compounds, including flavonoids, phenolic acids, alkaloids, terpenoids, proteins, and carbohydrates.

These phytochemicals play a dual role in nanoparticle synthesis: they act as reducing agents that convert metal ions into their corresponding nanoparticles, and as stabilizing or capping agents that prevent aggregation and enhance nanoparticle stability [4]. The exact composition of plant extracts varies depending on species, geographical location, and extraction methods, which can influence the size, shape, and functionality of the synthesized nanoparticles, a wide variety of metal and metal oxide nanoparticles have been successfully synthesized using plant extracts. Common examples include silver (Ag), gold (Au), copper (Cu), zinc oxide (ZnO), titanium dioxide (TiO₂), and iron oxide (Fe₃O₄) nanoparticles. These nanoparticles have demonstrated remarkable biological activities, including antimicrobial, antioxidant, anti-inflammatory, and anticancer properties. Such multifunctional capabilities make them highly attractive for biomedical applications, particularly in drug delivery systems, diagnostics, and therapeutic interventions, green-synthesized nanoparticles have shown great potential in addressing environmental challenges. Industrialization and urbanization have led to increased pollution, particularly in water and soil systems. Nanoparticles synthesized through green methods can be used for wastewater treatment, removal of heavy metals, degradation of organic

pollutants, and catalytic remediation processes [5]. Their high reactivity and surface functionality enable efficient interaction with contaminants, making them effective tools for environmental cleanup, several challenges remain in the field of green nanoparticle synthesis. One of the primary concerns is the lack of standardization in synthesis protocols, which leads to variability in nanoparticle characteristics. Furthermore, large-scale production remains a significant hurdle due to difficulties in maintaining consistency and efficiency [6]. There is also a need for comprehensive toxicity studies to ensure the safe use of these nanoparticles, especially in biomedical applications. Given the rapid advancements in nanotechnology and the increasing emphasis on sustainable practices, green synthesis using plant extracts represents a promising and rapidly evolving area of research. This review aims to provide a comprehensive overview of plant-mediated nanoparticle synthesis, including underlying mechanisms, influencing factors, characterization techniques, and diverse applications in biomedical and environmental fields. By addressing current challenges and future perspectives, this work seeks to highlight the potential of green nanotechnology in contributing to sustainable development and improved quality of life.

Table 1: Green Biosynthesis of Metal and Metal Oxide Nanoparticles Using Plant Extracts

Category	Description	Examples	Role of Plant Extracts
Metal Nanoparticles	Nanoparticles composed of pure metals	Ag, Au, Cu	Act as reducing and stabilizing agents
Metal Oxide Nanoparticles	Nanoparticles composed of metal oxides	ZnO, TiO ₂ , Fe ₃ O ₄	Facilitate oxidation-reduction reactions
Plant Sources	Leaves, roots, bark, flowers, fruits	Neem, Aloe vera, Green tea	Provide phytochemicals (flavonoids, alkaloids, phenols)
Synthesis Mechanism	Reduction of metal ions into nanoparticles	Ag ⁺ → Ag ⁰	Phytochemicals donate electrons
Stabilization (Capping)	Prevention of aggregation	Protein-coated nanoparticles	Biomolecules act as capping agents
Advantages	Eco-friendly, cost-effective, non-toxic	—	Eliminates need for harsh chemicals

Table 2: Multifunctional Applications of Biosynthesized Nanoparticles

Application Area	Specific Application	Mechanism of Action	Examples of Nanoparticles
Biomedical	Antimicrobial Activity	Disrupt microbial cell membranes	Ag, ZnO
Biomedical	Anticancer Therapy	Induce apoptosis in cancer cells	Au, TiO ₂
Biomedical	Drug Delivery	Targeted and controlled drug release	Fe ₃ O ₄ , Au
Biomedical	Anti-inflammatory	Reduce oxidative stress and inflammation	CuO, ZnO
Environmental	Wastewater Treatment	Adsorption and degradation of pollutants	TiO ₂ , Fe ₃ O ₄
Environmental	Heavy Metal Removal	Binding and removal of toxic ions	ZnO, Fe ₃ O ₄
Environmental	Dye Degradation	Photocatalytic breakdown of dyes	TiO ₂ , ZnO
Environmental	Pollution Remediation	Detoxification of contaminants	Ag, CuO

2. Green Synthesis of Nanoparticles

Green synthesis of nanoparticles using plant extracts has emerged as a sustainable and environmentally friendly alternative to conventional physical and chemical synthesis methods. This approach utilizes naturally occurring phytochemicals present in plants to reduce metal ions into nanoparticles while simultaneously stabilizing them. The method is simple, cost-effective, and does not require high energy input or toxic reagents, making it highly suitable for large-scale applications.

2.1 Role of Plant Extracts

Plant extracts play a crucial role in the biosynthesis of nanoparticles due to the presence of a wide variety of bioactive compounds. These include flavonoids, terpenoids, polyphenols, alkaloids, proteins, and enzymes, each contributing to different stages of nanoparticle formation. These phytochemicals possess strong reducing potential and are capable of converting metal ions into their corresponding

zero-valent or oxide nanoparticle forms [7]. Flavonoids and polyphenols are particularly important due to their antioxidant properties, which enable them to donate electrons and facilitate the reduction of metal ions such as Ag⁺, Au³⁺, and Cu²⁺. Terpenoids and alkaloids also contribute to reduction and stabilization processes, while proteins and enzymes act as capping agents that bind to the nanoparticle surface, enhancing stability and preventing agglomeration, plant-derived biomolecules provide a natural coating around nanoparticles, which improves their biocompatibility and functional properties. This capping layer also prevents aggregation, ensuring uniform particle size distribution and prolonged stability. The composition of plant extracts may vary depending on species, geographical origin, and extraction method, which in turn influences the morphology, size, and functionality of the synthesized nanoparticles.

2.2 Mechanism of Synthesis

The green synthesis of nanoparticles generally follows a well-defined mechanism consisting of three main stages: reduction, nucleation, and growth with stabilization. In the reduction phase, metal ions present in precursor solutions are reduced to their elemental or oxide forms by phytochemicals present in the plant extract. For instance, silver ions (Ag^+) are reduced to metallic silver (Ag^0) through electron donation by phenolic compounds. This step is critical as it initiates nanoparticle formation [8]. The second stage, nucleation, involves the aggregation of reduced atoms to form small clusters or nuclei. These nuclei serve as seeds for further growth. The rate of nucleation significantly affects the size and uniformity of the nanoparticles. Rapid nucleation typically results in smaller and more uniform particles, growth and stabilization, the nuclei grow into fully formed nanoparticles through processes such as coalescence and Ostwald ripening. Simultaneously, biomolecules present in the plant extract adsorb onto the nanoparticle surface, acting as stabilizing or capping agents. This prevents further aggregation and controls the shape and size of the nanoparticles. The balance between growth and stabilization determines the final physicochemical properties of the nanoparticles.

3. Types of Nanoparticles Synthesized Using Plants

Plant-mediated green synthesis has been successfully employed to produce a wide range of metal and metal oxide nanoparticles with diverse applications. These nanoparticles exhibit unique physicochemical and biological properties that make them suitable for use in medicine, environmental remediation, catalysis, and agriculture.

3.1 Metal Nanoparticles

Metal nanoparticles are among the most widely studied nanomaterials synthesized using plant extracts. Common examples include silver (AgNPs), gold (AuNPs), and copper (CuNPs). Silver nanoparticles are particularly well known for their strong antimicrobial properties and are widely used in medical devices, wound dressings, and coatings [9]. Gold nanoparticles exhibit excellent optical properties and are extensively used in biosensing, imaging, and targeted drug delivery systems. Copper nanoparticles are valued for their catalytic activity and cost-effectiveness, making them suitable for industrial and environmental applications. These metal nanoparticles demonstrate enhanced reactivity due to their large surface area and can interact effectively with biological systems, contributing to their multifunctional applications.

3.2 Metal Oxide Nanoparticles

Metal oxide nanoparticles synthesized via plant extracts include zinc oxide (ZnO), titanium dioxide (TiO_2), and iron oxide (Fe_3O_4) nanoparticles. These nanomaterials possess unique optical, magnetic, and catalytic properties.

Zinc oxide nanoparticles are widely recognized for their antibacterial, UV-blocking, and photocatalytic properties, making them useful in cosmetics, pharmaceuticals, and environmental cleanup [10]. Titanium dioxide nanoparticles are known for their strong photocatalytic activity and are commonly used in water purification and pollutant degradation. Iron oxide nanoparticles exhibit magnetic properties, which enable their application in targeted drug delivery, magnetic resonance imaging (MRI), and environmental remediation, both metal and metal oxide nanoparticles synthesized through green methods exhibit superior functionality, enhanced stability, and improved biocompatibility, making them highly promising for diverse scientific and industrial applications.

4. Factors Affecting Green Synthesis

The green synthesis of nanoparticles is influenced by several physicochemical parameters that play a critical role in determining their size, shape, stability, and overall functionality. Careful optimization of these parameters is essential to achieve nanoparticles with desired characteristics for specific applications. One of the most important factors is the pH of the reaction medium, which significantly affects the ionization of phytochemicals and their reducing ability. At different pH levels, the rate of reduction and stabilization varies, leading to differences in nanoparticle size and morphology. Generally, alkaline conditions favor faster reduction and the formation of smaller nanoparticles, whereas acidic conditions may result in slower reactions and larger particles.

Temperature is another crucial parameter influencing nanoparticle synthesis. Higher temperatures typically accelerate the reduction rate of metal ions and promote rapid nucleation, leading to smaller and more uniformly distributed nanoparticles. However, excessively high temperatures may destabilize phytochemicals and affect capping efficiency, thereby influencing particle aggregation. The concentration of plant extract determines the availability of bioactive compounds responsible for reduction and stabilization. Higher extract concentrations provide more reducing agents, resulting in faster synthesis and better stabilization. However, excessive concentrations may lead to agglomeration due to over-capping or uneven particle growth [11], the metal ion concentration plays a key role in nanoparticle formation. An optimal concentration is required to balance nucleation and growth processes. High metal ion concentrations may lead to rapid nucleation followed by aggregation, while low concentrations may result in incomplete reduction and low yield. Reaction time also affects nanoparticle synthesis, as it determines the extent of reduction and growth. Short reaction times may produce incomplete or unstable nanoparticles, whereas prolonged reaction times allow for complete reduction and stabilization but may also lead to particle aggregation or morphological changes, precise control and optimization of these parameters are essential for tailoring nanoparticle properties to meet specific biomedical and environmental requirements.

5. Characterization Techniques

Characterization of nanoparticles is a critical step in understanding their physicochemical properties, which directly influence their performance in various applications. A combination of analytical techniques is typically employed to obtain comprehensive information about nanoparticle size, shape, structure, composition, and surface chemistry [12]. UV-Visible spectroscopy (UV-Vis) is commonly used as a preliminary tool to confirm nanoparticle formation. The appearance of characteristic surface plasmon resonance (SPR) peaks indicates the reduction of metal ions and formation of nanoparticles. The position and intensity of these peaks provide insights into particle size and distribution [13]. X-ray diffraction (XRD) analysis is used to determine the crystalline structure and phase composition of nanoparticles. It provides information on crystallite size, lattice parameters, and degree of crystallinity, which are important for understanding material properties [14]. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are powerful imaging techniques that provide detailed information about nanoparticle morphology, size, and surface structure. TEM, in particular, offers high-resolution images that allow precise measurement of nanoparticle dimensions and shape. Fourier transform infrared spectroscopy (FTIR) is employed to identify functional groups present on the nanoparticle surface. This technique helps in understanding the role of phytochemicals in reduction and capping processes by detecting specific biomolecular interactions. Dynamic light scattering (DLS) is used to measure the hydrodynamic size and size distribution of nanoparticles in colloidal solutions. It also provides information about particle stability and aggregation behavior in suspension, these characterization techniques enable a comprehensive understanding of nanoparticle properties, which is essential for optimizing their synthesis and application.

6. Biomedical Applications

Green-synthesized nanoparticles have gained significant attention in the biomedical field due to their biocompatibility, reduced toxicity, and multifunctional properties. Their unique physicochemical characteristics enable them to interact effectively with biological systems, making them suitable for a wide range of therapeutic and diagnostic applications.

6.1 Antimicrobial Activity

One of the most prominent applications of green-synthesized nanoparticles is their antimicrobial activity against a wide spectrum of pathogenic microorganisms, including bacteria, fungi, and viruses. These nanoparticles exert their antimicrobial effects through multiple mechanisms. They disrupt microbial cell membranes, leading to leakage of cellular contents and cell death. Additionally, they generate reactive oxygen species (ROS), which induce oxidative stress and damage essential biomolecules such as lipids, proteins, and nucleic acids.

Nanoparticles can also penetrate microbial cells and interfere with DNA replication and protein synthesis, thereby inhibiting cell growth and proliferation [16]. The synergistic effect of these mechanisms makes nanoparticles highly effective against drug-resistant pathogens, offering a promising alternative to conventional antibiotics.

6.2 Anticancer Activity

Green-synthesized nanoparticles have shown considerable potential in cancer therapy due to their ability to selectively target cancer cells while minimizing damage to normal tissues. These nanoparticles induce apoptosis (programmed cell death) through the generation of oxidative stress and activation of cellular signaling pathways [7-10]. Furthermore, nanoparticles can be functionalized with targeting ligands to enhance their specificity toward cancer cells. This targeted approach improves therapeutic efficacy and reduces side effects commonly associated with conventional chemotherapy. Their small size also enables efficient cellular uptake and accumulation in tumor tissues via enhanced permeability and retention (EPR) effect.

6.3 Antioxidant Properties

Nanoparticles synthesized using plant extracts exhibit significant antioxidant activity due to the presence of phytochemical capping agents. These nanoparticles can scavenge free radicals and reduce oxidative stress, which is associated with various chronic diseases such as cancer, cardiovascular disorders, and neurodegenerative conditions [9-12]. The antioxidant potential of these nanoparticles enhances their therapeutic value and supports their use in preventive and protective healthcare applications.

6.4 Drug Delivery Systems

Nanoparticles serve as efficient carriers for drug delivery systems due to their small size, large surface area, and ability to be functionalized with specific ligands. Green-synthesized nanoparticles offer additional advantages such as biocompatibility and reduced toxicity. They enable targeted and controlled drug release, improving drug bioavailability and therapeutic efficiency while minimizing adverse effects [14]. Nanoparticle-based drug delivery systems are particularly useful in the treatment of cancer, infectious diseases, and chronic disorders, where precise targeting and sustained release are critical.

7. Environmental Applications

Green-synthesized metal and metal oxide nanoparticles have gained considerable attention in environmental applications due to their high reactivity, large surface area, and eco-friendly synthesis. Their unique physicochemical properties enable efficient interaction with pollutants, making them highly effective for environmental remediation and sustainability.

7.1 Wastewater Treatment

One of the most significant applications of green nanoparticles is in wastewater treatment.

Rapid industrialization has led to the discharge of various toxic substances into water bodies, including heavy metals, organic pollutants, and synthetic dyes. Green-synthesized nanoparticles offer an efficient and sustainable solution for removing these contaminants. Nanoparticles such as silver, iron oxide, and zinc oxide exhibit excellent adsorption capacity and catalytic activity. They can effectively bind and remove heavy metals like lead, cadmium, and mercury from contaminated water. In addition, they facilitate the degradation of organic pollutants and toxic dyes through oxidation-reduction reactions [17]. Their small size and high surface reactivity enhance pollutant removal efficiency, making them suitable for advanced water purification systems.

7.2 Catalytic Degradation

Green nanoparticles act as efficient catalysts in the degradation of hazardous compounds, including industrial dyes, pesticides, and pharmaceutical residues. Their catalytic properties enable the breakdown of complex pollutants into less toxic or non-toxic substances. Metal oxide nanoparticles such as titanium dioxide (TiO₂) and zinc oxide (ZnO) are widely used in photocatalytic degradation processes [18]. Under light irradiation, these nanoparticles generate reactive oxygen species (ROS), which oxidize and degrade organic contaminants. This photocatalytic activity makes them highly effective for treating industrial effluents and reducing environmental pollution.

7.3 Environmental Remediation

In addition to wastewater treatment, green-synthesized nanoparticles play a vital role in soil and environmental remediation. They are used to remove contaminants from soil through adsorption, reduction, and catalytic transformation processes. Iron oxide nanoparticles, for example, are particularly effective in immobilizing heavy metals and reducing their bioavailability in contaminated soils. Similarly, nanoparticles can degrade persistent organic pollutants and improve soil quality. Their eco-friendly nature ensures minimal environmental impact, making them suitable for sustainable remediation strategies.

8. Advantages of Green Synthesis

Green synthesis of nanoparticles offers several advantages over conventional physical and chemical methods, making it an attractive approach for researchers and industries, it is eco-friendly and non-toxic, as it eliminates the use of hazardous chemicals and reduces environmental pollution [19]. The use of plant extracts ensures that the synthesis process is safe for both humans and ecosystems, the method is cost-effective, as it utilizes readily available plant materials and does not require expensive equipment or high energy input. This makes it particularly suitable for large-scale production in resource-limited settings. Another important advantage is biocompatibility, which makes green-synthesized nanoparticles suitable for biomedical applications such as drug delivery and therapeutic treatments.

The natural capping agents derived from plant extracts enhance their compatibility with biological systems, the process is scalable with proper optimization, allowing for potential industrial applications. The elimination of toxic reagents also simplifies downstream processing and waste management, green synthesis represents a sustainable and efficient alternative that aligns with the principles of green chemistry and environmental conservation.

9. Challenges and Limitations

Despite its numerous advantages, green synthesis of nanoparticles faces several challenges that need to be addressed for widespread application. One of the major limitations is the lack of standardization in synthesis protocols. Variations in plant species, extraction methods, and reaction conditions lead to inconsistencies in nanoparticle properties, affecting reproducibility. The variability in plant extract composition is another critical issue. The concentration and type of phytochemicals can vary depending on environmental conditions, season, and plant part used, which influences nanoparticle synthesis and characteristics, large-scale production remains a challenge due to difficulties in maintaining uniformity and efficiency during scale-up processes. Developing reliable and reproducible methods for industrial-scale synthesis is essential [19]. Stability and aggregation issues also pose significant challenges, as nanoparticles tend to agglomerate over time, reducing their effectiveness and shelf life. Improved stabilization techniques are required to enhance long-term usability, there is a need for comprehensive toxicity assessment to ensure the safe application of nanoparticles, particularly in biomedical and environmental contexts. Understanding their interactions with living systems and ecosystems is crucial for minimizing potential risks.

10. Future Perspectives

The future of green nanoparticle synthesis is promising, with numerous opportunities for advancement and innovation. To fully realize its potential, future research should focus on gaining a deeper mechanistic understanding of synthesis pathways, including the role of specific phytochemicals in reduction and stabilization processes. Developing standardized protocols is essential to ensure reproducibility and consistency across different studies. This will facilitate comparison of results and accelerate progress in the field. Efforts should also be directed toward scaling up production processes for industrial applications. This includes optimizing reaction conditions, improving yield, and ensuring cost-effectiveness without compromising nanoparticle quality, clinical validation of green-synthesized nanoparticles is necessary to establish their safety and efficacy. This will pave the way for their integration into modern healthcare systems, the integration of green nanotechnology with advanced fields such as nanomedicine, biosensors, and smart delivery systems holds great potential.

Combining these technologies can lead to the development of innovative solutions for disease diagnosis, treatment, and environmental monitoring.

11. Conclusion

Green biosynthesis of metal and metal oxide nanoparticles using plant extracts represents a highly promising and sustainable approach in the field of nanotechnology. This method offers significant advantages over conventional synthesis techniques, particularly in terms of environmental safety, cost efficiency, and biocompatibility. By utilizing naturally occurring phytochemicals, green synthesis eliminates the need for toxic chemicals and energy-intensive processes, aligning with global sustainability goals. The synthesized nanoparticles demonstrate remarkable multifunctional properties, making them suitable for a wide range of applications. In the biomedical field, they exhibit strong antimicrobial, anticancer, antioxidant, and drug delivery capabilities. In environmental applications, they play a crucial role in wastewater treatment, pollutant degradation, and soil remediation, several challenges, including issues related to scalability, reproducibility, and toxicity, must be addressed to ensure their safe and effective use. Continued interdisciplinary research, technological innovation, and standardization efforts will be essential to overcome these limitations, green nanotechnology holds immense potential for developing innovative, safe, and efficient solutions that contribute to sustainable development, environmental protection, and improved human health.

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