International Journal of
Photochemistry and Photochemical Research

Volume 3, Issue 1, 2025
January–June
DOI Journal: 10.37591/IJPPR

https://journals.stmjournals.com/ijppr

Review IJPPR

Sustainable Innovations in Green Nanotechnology for Nanoparticle Synthesis

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Abstract

His approach has diverse applications across industries such as pharmaceuticals, energy, electronics, and bioengineering. Compared to conventional methods, biologically driven nanoparticle synthesis, particularly utilizing green chemistry principles, offers a safer, eco-friendly, non-toxic, and cost-effective alternative. Metal nanoparticles are commonly synthesized through top-down and bottom-up strategies using physical, chemical, and biological methodologies. This review explores the environmentally friendly synthesis, detailed characterization, and diverse applications of biologically derived metal nanoparticles, with a focus on silver, gold, iron, selenium, and copper. These nanoparticles have gained considerable attention due to their sustainable production methods, adaptable physicochemical attributes, and extensive use in biomedical and environmental sectors. Advanced analytical techniques such as UV-Vis spectrophotometry, Fourier-transform infrared spectroscopy (FT-IR), scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and atomic force microscopy (AFM) are essential for assessing their structural, morphological, and surface characteristics. Their potential applications span antimicrobial therapy, drug delivery, cancer treatment, water purification, and pollutant remediation, showcasing their multifunctional significance.

Keywords: Green synthesis, silver nanoparticles (AgNPs), plant extracts, nanoparticle characterization, biomedical applications

INTRODUCTION

Plants contain various phytochemical compounds, including phenolics, terpenoids, polysaccharides, and flavonoids, which possess oxidation-reduction properties. These compounds are ideal for nanoparticle synthesis [1-11]. However, phytochemical compound-based nanoparticle synthesis requires precise knowledge of the specific phytochemical components necessary for stabilized nanoparticle production [12]. Plant secondary metabolites, particularly polyphenols, play a crucial role in the green synthesis process. This practice is regarded as advanced, safe, cost-effective, reproducible, and stable [13]. Compared to other biological methods utilizing bacteria, fungi, actinomycetes, and algae, plant-based green synthesis presents several advantages [14]. Various plant parts, such as roots, stems, leaves, seeds, and fruits, are involved in the synthesis due to their significant phytochemical content [15]. The process entails washing the plant material with tap or distilled water, followed by extraction through squeezing and filtration, after which specific salt solutions are introduced. The addition of metallic salts leads to nanoparticle formation. This method facilitates the synthesis of a wide range of metallic nanoparticles [16-17].

The biosynthesis approach is vital for minimizing harmful by-products and promoting sustainable

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Received Date: February 10, 2025
Accepted Date: February 14, 2025
Published Date: February 15, 2025

Citation: Oluwanifemi. Sustainable Innovations in Green Nanotechnology for Nanoparticle Synthesis. International Journal of Photochemistry and Photochemical Research, Volume 3, Issue 1. 2025; 3(1): 1–7p.

development. These natural sources act as reducing and stabilizing agents, offering an eco-friendly approach to nanoparticle production. Sharma et al. (2015) highlighted the green synthesis, detailed characterization, and diverse applications of metal nanoparticles, particularly in the removal of pollutant dyes from wastewater. Their study demonstrated the efficiency of these nanoparticles in degrading various dye contaminants, including azo dyes, acid dyes, and cationic dyes, thereby emphasizing their potential in environmental remediation and sustainable water treatment solutions. Metallic nanoparticles contribute significantly to purifying water bodies, such as rivers, lakes, and streams, enhancing aquatic ecosystems. Green-synthesized nanoparticles are also applied in treating environmental pollutants. Previous research highlights that the catalytic properties of certain nanoparticles effectively reduce the toxicity of environmental contaminants [18–20]. The efficacy of metallic nanoparticles against human pathogenic microbes further establishes their significance in biomedical applications [21-25].

Top-Down and Bottom-Up Approaches

Nanoparticles synthesized through biological systems offer numerous benefits, including non-toxicity, high yield production, ease of scaling, and well-defined morphology. As a result, this innovative approach to nanoparticle production has gained significant interest. Green synthesis techniques have been established as highly effective, ensuring safety, eco-friendliness, and easy handling [26–29], summarizing their biomedical and agricultural applications (Saratale et al. 2018a). The synthesis of green nanoparticles falls into two categories: "top-down" and "bottom-up" approaches, based on how nanoparticles are formed. In the "top-down" approach, nanoparticles are initially larger, requiring mechanical methods or acid treatments to reduce their size. This method typically involves complex analytical techniques, including thermal decomposition, mechanical/ball-milling, lithographic methods, laser ablation, and sputtering. Conversely, the "bottom-up" approach begins at the atomic or molecular level, forming nanoparticles through various processes such as chemical vapor deposition (CVD), sol-gel methods, spinning, and pyrolysis [30].

Factors Influencing the Green Synthesis of Various Nanoparticles: These environmental factors significantly impact the synthesis and optimization of metallic nanoparticles [31].

Temperature

Numerous studies explore the effects of temperature on nanoparticle synthesis. Temperature plays a critical role in determining the size, shape, and yield of nanoparticles. Different shapes (triangular, octahedral, spherical, and rod-like) and sizes can be controlled by adjusting temperature. Higher temperatures accelerate reaction rates and nucleation center formation [32-34].

pH

pH is a crucial factor in nanoparticle synthesis, influencing nucleation center formation and overall morphology. Higher pH levels increase the number of nucleation centers, thereby enhancing nanoparticle formation. It has been observed that pH significantly affects the structural characteristics of nanoparticles [35, 36].

Reaction Time

Reaction time is a key parameter that influences nanoparticle morphology. Alongside temperature and pH, it plays a crucial role in determining nanoparticle size, shape, and yield. Karade et al. [37] highlighted the importance of reaction time in the synthesis of magnetic nanoparticles [38-40].

FT-IR Spectroscopy

Fourier-transform infrared (FT-IR) spectroscopy identifies functional groups in biomolecules involved in nanoparticle synthesis. This technique works by passing infrared radiation through the sample, where certain wavelengths are absorbed while others transmit through, generating a spectrum that reflects the molecular composition [41]. FT-IR is widely used due to its simplicity, cost-effectiveness, and non-destructive nature. It is particularly valuable for detecting biomolecules that facilitate nanoparticle formation, such as reducing agents in the transformation of silver nitrate into silver nanoparticles [42].

UV-Vis Spectrophotometry

UV-Vis spectroscopy is a fundamental tool for nanoparticle characterization, especially for determining their size within the 2–100 nm range. The absorption spectrum generally lies within the 300–800 nm range, with studies showing that wavelengths between 200–800 nm are optimal for nanoparticle size analysis [43, 44]. The technique is fast, reliable, and commonly used to monitor nanoparticle synthesis by observing shifts in absorbance peaks, which indicate variations in size and aggregation.

Scanning Electron Microscopy (SEM)

SEM provides detailed insight into the shape, size, surface morphology, and distribution of nanoparticles. By using high-energy electron beams, SEM produces high-resolution images that reveal nanoparticle structure at the nanometer scale. This method is particularly effective in visualizing agglomeration, porosity, and surface roughness, offering critical data for optimizing nanoparticle applications in biomedical, environmental, and industrial fields. It also assesses morphological changes before and after treatment, which is useful for studying the antimicrobial effects of nanoparticles [39, 40].

X-ray Diffraction (XRD)

XRD analysis determines atomic structures and crystalline nanoparticle size. It provides qualitative and quantitative insights into materials [45-47].

1. Atomic Force Microscopy (AFM)
2. AFM characterizes nanoparticle size, shape, and surface features [38, 40].
3. Transmission Electron Microscopy (TEM)
4. TEM analyzes nanoparticle crystal structures and sizes at the nanoscale level [39, 40].
5. Annular Dark-Field Imaging (HAADF)
6. HAADF imaging studies nanoparticle interactions with bacteria and provides insights into their size distribution during biological interactions [39, 40].
7. Inductively Coupled Plasma (ICP) Spectroscopy

ICP spectrometry determines metal concentrations in deionized and nanoparticle solutions. ICP mass spectrometry (ICP-MS) and ICP emission spectroscopy (ICP-ES) assess metal nanoparticle concentrations [39, 40].

Green Synthesis of Metal Nanoparticles and Their Applications

Biologically synthesized nanoparticles exhibit superior pharmacological activity compared to physicochemical methods. Various plants, including neem (Azadirachta indica), tulsi (Ocimum tenuiflorum), curry leaves (Murraya koenigii), guava (Psidium guajava), and mango (Mangifera indica), have been used for green nanoparticle synthesis [48].

Figure 3). These properties make green nanoparticles highly beneficial for biomedical applications [49]. In agriculture, green nanotechnology reduces environmental harm and lowers fertilizer costs. [50].

Applications

Nanoparticle Synthesis Using Plant Extracts

Various plant parts, including roots, stems, latex, leaves, and seeds, have been extensively utilized for the green synthesis of metal nanoparticles. These plant-based methods offer an eco-friendly, cost-effective, and sustainable approach to nanoparticle production. Numerous studies have demonstrated the successful synthesis of silver nanoparticles (AgNPs) using plant extracts, highlighting their potential applications in biomedical and environmental fields [43-45] the synthesis of silver nanoparticles using *French tamarisk* (*Tamarix gallica*), demonstrating the plant's efficiency in reducing silver ions.

Similarly, Chinnappan et al. *Nanoparticle Synthesis Methods: Silver Nanoparticles as a Simple and Cost-Effective Approach*

Green synthesis methods utilizing plant extracts serve as an efficient and low-cost alternative to chemical and physical synthesis techniques. These methods harness bioactive compounds such as flavonoids, tannins, and polyphenols, which act as reducing and stabilizing agents, ensuring controlled nanoparticle synthesis. The simplicity, biocompatibility, and environmental sustainability of plant-mediated AgNP synthesis make it a promising strategy for diverse applications, including antimicrobial treatments, drug delivery, biosensing, and wastewater remediation. Lakshmanan et al. reported that the plant extract of the Asian spider flower (*Cleome viscosa*) facilitates the synthesis of silver nanoparticles, demonstrating an enhanced ability to reduce silver nitrate to metallic silver. Similarly, silver nanoparticles have been synthesized using oregano (*Origanum vulgare L.*) in an aqueous solution, where the reduction of Ag^{+} ions is indicated by a color change from light brown to dark brown. [46-53] lectron microscopy (TEM). The study further confirmed that banana peel extract acts as an efficient capping and reducing agent, as characterized by TEM, SEM, FE-SEM, DLS, and SAED techniques. heir high surface area allows efficient ligand binding, making them valuable in antimicrobial applications. Silver nitrate is commonly utilized for its antimicrobial properties, and silver nanoparticles are emerging as a powerful alternative in combating harmful microbes. These nanoparticles exhibit exceptional physical, chemical, and biological properties, providing broad-spectrum antimicrobial activity, non-toxic behavior, anticancer potential, and cost-effective production. Several studies have demonstrated the potent silver nanoparticles function by disrupting the bacterial cell wall and interfering with the overall synthesis process Martinez et al. (2018) investigated the bactericidal properties of silver nanoparticles, emphasizing that their effectiveness depends on size and shape. Additionally, silver nanoparticles synthesized from *Leucaena leucocephala* have shown promising antibacterial, antimycobacterial, and antimalarial properties against *Streptococcus pyogenes [54-55]*.

Toxicity Aspects of Metal Nanoparticles:

This process triggers pro-inflammatory responses and can lead to cellular damage, including DNA and protein degradation, lysosomal hydrolase activation, mitochondrial dysfunction, apoptosis, cytoplasmic disorder, altered ATP levels, and increased membrane permeability. The toxicity effects vary depending on nanoparticle size, type, individual properties, and particle mixtures [56].

CONCLUSION

Nanoparticles serve as a valuable tool in diverse fields, including food, agriculture, medicine, electronics, and energy harvesting. Their synthesis can be achieved through physical, chemical, and biological methods, with green synthesis emerging as the most efficient and eco-friendly approach. This method is non-toxic, cost-effective, and sustainable. This review highlights various synthesis methods, characterization techniques, and applications of plant-based metal and metal oxide nanoparticles, emphasizing their antibacterial, antifungal, antimalarial, antioxidant, anticancer, and photocatalytic properties. The findings strongly support the use of green synthesis to develop environmentally and biomedically beneficial nanoparticles. Moving forward, our research group aims to focus on synthesizing various types of green nanoparticles for applications across multiple sectors, including pharmaceuticals, medicine, environmental science, aquaculture, and agriculture.

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