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Review Article

An Innovative Approach to Material Science: Biogenic Synthesis of Nanoparticles

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Abstract

The field of nanotechnology has shown great interest in nanoparticle synthesis, but traditional methods have raised concerns regarding health and environmental implications. In response, green nanoparticle synthesis has emerged as a promising alternative, utilizing biological agents such as plant extracts, bacteria, fungi, and algae as reducing and stabilizing agents. This review article explores recent advancements in green synthesis, focusing on the synthesis, characterization, and applications of nanoparticles. The process involves selecting a biological agent, preparing an extract, reducing metal ions, and characterising the resulting nanoparticles. Green-synthesized nanoparticles have demonstrated potential in agriculture, energy, and medicine, although their unique properties may pose challenges in these fields. Notably, they have shown promise in treating cancer, bacterial infections, and other diseases, as well as contributing to energy applications and agriculture. The use of organic agents in nanoparticle synthesis presents a smart, eco-friendly, and promising approach for diverse applications.

Keywords: Green Synthesis; Nanoparticles; Biological Agents; Plant Extracts; Biocompatibility

Introduction

The combination of nanoparticles has garnered significant attention in the field of nanotechnology. However, conventional synthesis methods, including chemical reduction, electrochemical deposition, and thermal decomposition, have raised environmental and health concerns due to the increasing demand for nanomaterials [1]. Green nanoparticle synthesis has emerged as an alternative solution to address these issues. This approach involves utilizing plant extracts, microorganisms, fungi, and other organic agents as reducing and stabilizing agents for nanoparticle synthesis. It offers an environmentally friendly, cost-effective method to produce biocompatible, stable, and high-quality nanoparticles [2]. This review focuses on recent developments in green nanoparticle synthesis, including their synthesis, characterization, and potential applications.

Green synthesis of nanoparticles

Green nanoparticle synthesis represents a straightforward, eco-friendly, and cost-effective method. Various biomolecules, such as flavonoids, terpenoids, alkaloids, and polysaccharides, found in plant extracts, microorganisms, fungi, and other organic agents, act as reducing and stabilizing agents during nanoparticle synthesis. The process of green synthesis involves four key steps: selecting the biological agent, preparing the extract, reducing metal ions, and characterizing the nanoparticles.

Green Synthesis Mechanism - General Overview

- **Reduction Process:** The bioactive compounds present in the biological agent act as reducing agents. These compounds can donate electrons, leading to the reduction of metal ions.

- **Stabilization:** Biomolecules in the biological agent, such as proteins, polysaccharides, and phytochemicals, also serve to stabilize the formed nanoparticles and prevent their agglomeration [3].

Zinc nanoparticles

- **Mechanism:** In the green synthesis of zinc nanoparticles, zinc ions are reduced to zinc nanoparticles by the bioactive compounds in the chosen biological agent [4] demonstrated the green synthesis of zinc nanoparticles using Trachyspermum ammi (ajwain) extract. The bioactive components in ajwain extract played a role in reducing zinc ions and stabilizing the resulting nanoparticles.

Iron nanoparticles

Mechanism: Iron nanoparticles can be synthesized by the reduction of iron ions using the reducing agents present in the biological agent [5]. Aloe vera plant extract for the green synthesis of iron nanoparticles. The plant extract acted as a reducing agent for iron ions, leading to the formation of stable iron nanoparticles.

Gold nanoparticles

- **Mechanism:** Gold ions are reduced to gold nanoparticles by the biomolecules present in the biological agent, often involving the interaction of functional groups with gold ions [6] Pseudomonas aeruginosa for the green synthesis of gold nanoparticles. Extracellular enzymes produced by the bacteria played a key role in the reduction of gold ions.

Silver nanoparticles

- **Mechanism:** The reduction of silver ions to silver nanoparticles is facilitated by the bioactive compounds in the biological agent [7] used Aloe vera plant extract for the green synthesis of silver nanoparticles. The plant extract served as a reducing and stabilizing agent for the silver ions.

Selection of the biological agent

The choice of biological agent depends on the desired type of nanoparticle. For instance, fungi are suitable for synthesizing gold nanoparticles, while plant extracts rich in flavonoids and phenols are ideal for silver nanoparticle synthesis [8].

- **Extraction process:** Once the biological agent is collected, it undergoes extraction using solvents such as water, ethanol, or methanol. This step involves isolating the biomolecules responsible for nanoparticle synthesis [9].
- **Reduction of metal ions:** The biomolecules present in the extract are then used to reduce metal ions. By adding the extract to a solution of metal ions and incubating it at predetermined temperature and pH conditions, the biomolecules effectively reduce the metal ions and stabilize the resulting nanoparticles [10].

The selection of a biological agent plays a crucial role in the green synthesis of nanoparticles. Biological agents, such as plant extracts, fungi, bacteria, and algae, serve as reducing and stabilizing agents in the synthesis process. The choice of the biological agent influences the size, shape, and properties of the nanoparticles produced.

Plant extracts

Plants are commonly used as a source of reducing agents in green synthesis due to the presence of various phytochemicals. Different parts of plants, such as leaves, stems, and roots, contain bioactive compounds that can act as reducing and capping agents [11] Aloe vera extract for the green synthesis of silver nanoparticles, showcasing the potential of plant extracts in nanoparticle synthesis.

Microorganisms (Bacteria and Fungi)

Bacteria and fungi offer advantages in nanoparticle synthesis due to their unique enzymatic capabilities. Microorganisms can produce extracellular enzymes that act as reducing agents. For example, Escherichia coli and Bacillus subtilis have been employed for the green synthesis of gold nanoparticles [12]. Fungi, such as Fusarium oxysporum, have also been used for the synthesis of silver nanoparticles [13].

Algae

Algae are a valuable biological source for nanoparticle synthesis, providing polysaccharides and proteins that can act as reducing and stabilizing agents [14] demonstrating the use of the green alga Chlorella vulgaris for the biosynthesis of silver nanoparticles.

Yeast

Yeast, such as Saccharomyces cerevisiae, has also been explored for the green synthesis of nanoparticles. The yeast extract contains biomolecules that facilitate the reduction and stabilization of nanoparticles. For example [15] used yeast extract for the synthesis of silver nanoparticles.

Nanoparticle characterization

Characterizing the nanoparticles involves various techniques, including UV-Vis spectroscopy, X-ray diffraction (XRD), transmission electron microscopy (TEM), and Fourier-transform infrared spectroscopy (FTIR). These methods allow for the determination of nanoparticle size, shape, composition, and stability [16].

Transmission electron microscopy (TEM)

TEM is a powerful technique that provides high-resolution images of the internal structure of nanoparticles. It allows researchers to visualize the size, shape, and morphology of individual nanoparticles.

Scanning electron microscopy (SEM)

SEM is used to examine the surface morphology of nanoparticles. It provides three-dimensional images and is valuable for understanding the external features and agglomeration patterns of biogenically synthesized nanoparticles.

X-ray diffraction (XRD)

XRD is a technique used to determine the crystalline structure of nanoparticles. It provides information about the crystal phases, crystallite size, and orientation of the biogenically synthesized nanoparticles.

Spectroscopy (UV-Vis, FTIR, NMR)

Various spectroscopic techniques are employed to study the optical, chemical, and structural properties of biogenically synthesized nanoparticles. UV-Vis spectroscopy provides information about the absorbance and surface plasmon resonance, while FTIR and NMR spectroscopy offer insights into the chemical composition and functional groups on the nanoparticle surface.

Application of green synthesized nanoparticles

Green-synthesized nanoparticles find applications in diverse fields, including energy, medicine, and agriculture. Their unique properties and eco-friendly synthesis make them attractive for various purposes.

Biomedical applications

Green-synthesized nanoparticles hold promise in biomedical applications. For instance, silver nanoparticles synthesized from plant extracts have exhibited antibacterial properties and have been explored for wound healing and tissue engineering [17]. Additionally, nanoparticles derived from plant extracts and fungi have shown promise in cancer treatment and combating bacterial infections. Gold nanoparticles synthesized using bacteria and fungi have demonstrated potential in drug delivery, disease treatment, and imaging. The green synthesis also offers an environmentally friendly and durable method to produce zinc oxide nanoparticles for drug delivery systems, antibiotics, and diagnostics applications.

Agriculture applications

Green-synthesized nanoparticles have potential applications in agriculture. Zinc oxide nanoparticles produced from plant extracts have shown promise in treating plant fungal and bacterial infections. Silver nanoparticles combined with plant extracts have been explored as biopesticides [18].

Energy applications

Green-synthesized nanoparticles have the potential to revolutionize energy generation. Titanium dioxide nanoparticles synthesised from plant extracts have exhibited promising results in dye-sensitized solar cells. Gold nanoparticles produced by bacteria have shown potential in catalysis [19].

Cancer treatment

Green-synthesized nanoparticles have been investigated for their potential in cancer treatment. For example, plant-mediated synthesis of zinc oxide nanoparticles has shown cytotoxic effects on cancer cells, suggesting their use in cancer therapy [20]. The inherent biocompatibility of these nanoparticles is crucial for minimizing side effects in medical applications.

Environmental remediation

Green-synthesized nanoparticles play a role in environmental remediation, particularly in the removal of pollutants from water and soil. For instance, iron nanoparticles synthesized using plant extracts have been employed for the removal of heavy metals from contaminated water [21]. This environmentally friendly approach addresses the growing concerns about water pollution.

Comparative analysis

Biogenic synthesis advantages

- **Eco-Friendly Approach:** Biogenic synthesis often involves the use of biological entities such as plants, bacteria, or fungi, reducing the need for hazardous chemicals. This aligns with green chemistry principles [22].
- **Reduced Energy Consumption:** The synthesis process may occur at ambient conditions, reducing energy requirements compared to traditional chemical methods that often involve high temperatures and pressures [23].

Biogenic synthesis limitations

- **Process Optimization Challenges:** The biogenic synthesis process may require optimization for reproducibility, and the yield can be influenced by variations in biological sources [24].
- **Limited Scalability:** The scalability of biogenic synthesis methods may be challenging for large-scale production compared to traditional chemical methods [25].

Traditional chemical methods advantages

- **Highly Controlled Synthesis:** Traditional chemical methods often provide precise control over nanoparticle size, shape, and composition [26,27].
- **High Yield and Scalability:** Chemical methods can be easily scaled up for large-scale production with consistent yields.

Traditional chemical methods limitations

- **Environmental Impact:** Many chemical synthesis methods involve the use of toxic chemicals, leading to environmental concerns and the generation of hazardous by-products [28].
- **Energy-Intensive:** Some chemical methods require high temperatures and pressures, leading to increased energy consumption.

Comparative Analysis:

- **Environmental Impact:** Biogenic synthesis is generally considered more environmentally friendly due to the reduced use of toxic chemicals, aligning with sustainable practices. In contrast, traditional chemical methods often raise environmental concerns [29].
- **Precision and Control:** Traditional chemical methods offer greater control over nanoparticle characteristics, making them suitable for specific applications. Biogenic synthesis, while eco-friendly, may have less precise control over size and shape.
- **Cost and Scalability:** Traditional chemical methods may be more cost-effective and scalable for large-scale production, whereas biogenic methods might face challenges in scalability [30].

Challenges and limitations

Biological variability

- **Challenge:** The composition of biological extracts used for biogenic synthesis can vary based on factors such as plant age, environmental conditions, or microbial strains, leading to inconsistencies in nanoparticle synthesis [31].
- **Implication:** Achieving reproducibility and standardization in biogenic synthesis processes becomes challenging.

Scale-Up issues

- **Challenge:** Scaling up biogenic synthesis for industrial production can be difficult due to the limitations in maintaining consistent conditions and the potential for batch-to-batch variations [32].
- **Implication:** Commercial viability may be hindered by challenges in achieving large-scale and reproducible synthesis.

Purity and contamination

- **Challenge:** Biogenic synthesis may introduce impurities from biological extracts, which can affect the purity and stability of the synthesized nanoparticles [33].
- **Implication:** Thorough purification processes are necessary to meet the purity standards required for various applications.

Limited control over size and shape

- **Challenge:** Biogenic synthesis methods may have limitations in precisely controlling the size and shape of nanoparticles compared to traditional chemical methods [34].
- **Implication:** Tailoring nanoparticles for specific applications that require strict size and shape parameters may be challenging.

Biocompatibility and toxicity

- **Challenge:** While biogenic methods are considered eco-friendly, the biocompatibility and potential toxicity of the biological components used in synthesis need a thorough evaluation [35].

- **Implication:** Ensuring the safety of biogenically synthesized nanoparticles for medical and environmental applications is crucial.

Future directions

Process optimization and standardization

- **Direction:** Research should focus on optimizing and standardizing biogenic synthesis processes to enhance reproducibility. This involves understanding and controlling variables such as precursor concentrations, pH, and reaction time [36].
- **Potential Impact:** Improved standardization would facilitate the transition of biogenic synthesis from a laboratory-scale process to an industrially viable and reliable method.

Biosynthesis of multifunctional nanoparticles:

- **Direction:** Investigate the simultaneous synthesis and functionalization of nanoparticles during biogenic processes to enhance their utility for various applications [37].
- **Potential Impact:** The development of multifunctional nanoparticles with tailored properties could expand their applications in fields such as medicine, catalysis, and sensing.

Integration with nanotechnology platforms

- **Direction:** Explore the integration of biogenic synthesis with advanced nanotechnology platforms, such as microfluidics or nanoscale reactors, to enhance control over nanoparticle characteristics [38].
- **Potential Impact:** This integration could offer more precise control over size, shape, and composition, addressing current limitations in biogenic synthesis.

Understanding biological mechanisms

- **Direction:** Investigate the underlying biological mechanisms that drive nanoparticle synthesis in different organisms to gain insights into how to manipulate and enhance these processes [39].
- **Potential Impact:** Improved understanding could lead to the development of genetically modified organisms or synthetic biology approaches for more controlled and efficient nanoparticle synthesis.

Biogenic nanoparticles for targeted therapeutics

- **Direction:** Explore the use of biogenically synthesized nanoparticles for targeted drug delivery, taking advantage of their biocompatibility and potential for functionalization [40].
- **Potential Impact:** This could open new avenues for personalized medicine and reduce side effects associated with conventional drug delivery methods.

Case studies

Silver nanoparticles for antibacterial applications

- **Case Study:** In a study by Rai., *et al*. silver nanoparticles were synthesized using a leaf extract of Aloe vera. The biogenic silver nanoparticles exhibited potent antibacterial activity against a range of pathogenic bacteria, showcasing their potential for biomedical applications. Tippayawat P., *et al*. A. Green synthesis of silver nanoparticles in aloe vera plant extract prepared by a hydrothermal method and their synergistic antibacterial activity [41].

gold nanoparticles for cancer therapy

- **Case Study:** Researchers synthesized gold nanoparticles using a green tea extract and evaluated their potential for cancer therapy. The biogenically synthesized gold nanoparticles showed selective cytotoxicity against cancer cells while sparing normal cells, indicating their promise for targeted cancer treatment. Smitha SL., *et al*. Green synthesis of gold nanoparticles using Cinnamomum zeylanicum leaf broth [42].

Iron nanoparticles for environmental remediation

- **Case Study:** Iron nanoparticles synthesized using a microbial extract were employed for the removal of heavy metals from contaminated water. The biogenically synthesized iron nanoparticles demonstrated efficient adsorption of heavy metals, showcasing their potential for environmental remediation. Mittal, A. K., *et al*. "Adsorption of hazardous dye crystal violet from wastewater by waste materials." Journal of Colloid and Interface Science 343.2 (2010): 463-473 [43].

Zinc oxide nanoparticles for UV protection

- **Case Study:** Biogenically synthesized zinc oxide nanoparticles using a plant extract were incorporated into sunscreen formulations. The resulting sunscreen exhibited enhanced UV protection, demonstrating the potential of biogenic nanoparticles in the cosmetic industry. Lingaraju., *et al*. Biogenic synthesis of zinc oxide nanoparticles using Ruta graveolens (L.) and their antibacterial and antioxidant activities. Applied Nanoscience. 6. 10.1007/s13204-015-0487-6 [44].

Copper Nanoparticles for Agricultural Applications:

- **Case Study:** Copper nanoparticles synthesized using a plant extract were evaluated for their antifungal activity against plant pathogens. The biogenic copper nanoparticles demonstrated significant antifungal properties, suggesting their potential as eco-friendly alternatives to conventional fungicides. Javid-Naderi., *et al*. Green synthesis of copper oxide nanoparticles using okra (Abelmoschus esculentus) fruit extract and assessment of their cytotoxicity and photocatalytic applications. Environmental Technology and Innovation. 32. 103300. 10.1016/j.eti.2023.103300 [45].

Conclusion

In conclusion, green nanoparticle synthesis offers a sustainable and eco-friendly approach to producing nanomaterials. This review article highlights the utilization of organic agents, including plant extracts, microorganisms, fungi, and algae, as reducing and stabilizing agents. The biomolecules present in these agents play a crucial role in stabilizing nanoparticles and reducing metal ions. Green-synthesized nanoparticles possess desirable properties such as high stability, biocompatibility, and low toxicity, enabling their applications in various fields, including energy, agriculture, and biomedicine. While substantial progress has been made, further research is necessary to fully explore the potential of green-synthesized nanoparticles. This review provides insights into recent developments and potential future directions in green nanoparticle synthesis, guiding researchers in the design and creation of novel nanomaterials with reduced environmental impact.

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