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GREEN SYNTHESIS OF NANOPARTICLES USING BIOLOGICAL RESOURCES: RECENT ADVANCES, APPLICATIONS AND CHALLENGES

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Abstract:

Nanotechnology has seen rapid growth over the past few decades, and with it, the importance of green nanotechnology has risen significantly. Green nanotechnology involves the eco-friendly synthesis of nanoparticles (NPs) using biological systems such as plants, animals, microorganisms, enzymes, and biomolecules. Biogenic synthesis offers advantages over traditional chemical methods, including lower toxicity, environmental sustainability, and cost-effectiveness. This review article highlights recent advancements in green nanotechnology, focusing on the biogenic synthesis of nanoparticles from various biological sources. The paper discusses the methods used for nanoparticle synthesis, the characterisation techniques employed to evaluate their properties, and the broad range of applications across diverse fields, including medicine, environmental remediation, and agriculture. Additionally, it addresses the challenges and limitations of biogenic nanoparticle synthesis and provides insight into future research directions. Through this, the review aims to shed light on the immense potential of green nanotechnology and its promising future for creating sustainable and environmentally friendly nanomaterials.

Keywords: *Green Nanotechnology, Biogenic Synthesis, Nanoparticles, Plant-Based Synthesis, Microorganism-Based Synthesis, Environmental Remediation.*

1. Introduction

Nanotechnology has revolutionised various fields, from medicine to electronics, due to the unique properties that materials exhibit at the nanoscale. One of the most prominent areas in nanotechnology is the synthesis of nanoparticles (NPs), which can exhibit a wide range of physical, chemical, and biological properties due to their small size and high surface area. Traditional methods of nanoparticle synthesis, such as chemical reduction and physical vapour deposition, often involve toxic chemicals and high energy inputs.

In recent years, green nanotechnology has emerged as a sustainable alternative, using natural, eco-friendly processes to produce nanoparticles. Biogenic synthesis, which involves using biological systems such as plants, animals, microorganisms, and enzymes, offers several advantages over conventional chemical methods, including lower toxicity, reduced environmental impact, and cost-effectiveness. This method aligns with the principles of green chemistry, minimising the use of toxic chemicals and reducing waste production.

The purpose of this review is to explore the advancements in the biogenic synthesis of nanoparticles, the various biological sources used, their characterisation techniques, and the applications of green-synthesised nanoparticles. Additionally, we will address the challenges and limitations of this approach and provide insights into the future prospects of biogenic synthesis in nanotechnology.

2. Methods of green synthesis of nanoparticles

The biogenic synthesis of nanoparticles leverages various biological systems to reduce metal salts into nanoparticles under mild conditions. These systems can be plant-based, animal-based, or microbial-based, and they offer a more sustainable and environmentally friendly approach to nanomaterials production.

2.1 Plant-based synthesis

Plant-based synthesis, also known as phytosynthesis, is one of the most widely explored methods for the production of nanoparticles. Plants contain a variety of biomolecules, such as polyphenols, flavonoids, and alkaloids, which can act as reducing agents for metal ions, leading to the formation of nanoparticles. The advantages of plant-based synthesis include the availability of plants, cost-effectiveness, and eco-friendliness. For example, green tea, neem leaves, and cinnamon have been used for the synthesis of gold, silver, and copper nanoparticles (1). Plant-based synthesis also has the benefit of producing biocompatible and less toxic nanoparticles, making them suitable for biomedical applications (2).

2.2 Animal-based synthesis

Animal-based synthesis often utilises substances like honey, silk, or proteins derived from animal tissues to mediate nanoparticle synthesis. Honey, in particular, has shown promise in the synthesis of gold and silver nanoparticles due to its rich composition of natural enzymes and sugars, which can reduce metal ions to nanoparticles. Silk proteins, derived from silkworms, are also used for their ability to provide structural stability to nanoparticles, making them useful for drug delivery systems (3). Animal-derived biomaterials are generally biocompatible and biodegradable, which makes them ideal candidates for use in medical applications.

2.3 Microbial synthesis

Microorganisms, including bacteria, fungi, and algae, are increasingly being used for the synthesis of nanoparticles due to their ability to produce nanoparticles with controlled sizes and shapes. Fungi such as *Aspergillus* and *Fusarium* are particularly efficient in nanoparticle synthesis, with the ability to reduce metal ions into stable nanoparticles with high surface area (4). Similarly, bacteria such as *Escherichia coli* and *Pseudomonas* have been employed to produce nanoparticles with specific characteristics, which can be utilised in fields like medicine and environmental remediation. The microbial approach offers scalability, ease of handling, and the potential for high-yield production.

2.4 Algae-based synthesis

Algae offer several advantages, including rapid growth rates and the ability to synthesise a wide range of nanoparticles. *Spirulina* and *Chlorella* are among the algae species used for green synthesis (5).

2.5 Enzyme and biomolecule-mediated synthesis

Enzymes and biomolecules such as proteins, peptides, and nucleic acids play a crucial role in the biogenic synthesis of nanoparticles. These molecules can act as both reducing and stabilising agents for metal ions, promoting the formation of nanoparticles under mild conditions. Enzyme-mediated synthesis offers the advantage of specificity, as enzymes can catalyse reactions with high precision, leading to the formation of nanoparticles with well-defined size and shape (6). This method is particularly advantageous for applications in medicine and diagnostics, where size and shape control is crucial.

3. Characterisation of biogenic nanoparticles

Characterising biogenic nanoparticles is crucial to understanding their physical, chemical, and biological properties. Several techniques are employed to determine the size, shape, surface charge, and composition of nanoparticles:

3.1 UV-Vis spectroscopy

UV-Vis spectroscopy is commonly used to monitor the formation of nanoparticles. The reduction of metal ions is accompanied by a characteristic surface plasmon resonance (SPR) peak, which can be observed through UV-Vis absorbance spectra. This technique is quick, easy to use, and provides preliminary information on nanoparticle formation (7).

3.2 Transmission electron microscopy (TEM)

TEM is one of the most powerful techniques for determining the size, shape, and morphology of nanoparticles. TEM allows for the visualisation of nanoparticles at high resolution and provides information on their distribution and aggregation (8).

3.3 Dynamic light scattering (DLS)

Dynamic light scattering (DLS) is used to measure the hydrodynamic size and zeta potential of nanoparticles in a solution. This technique is particularly useful for evaluating the stability and surface charge of nanoparticles, which are critical parameters for their applications in drug delivery and environmental remediation (9).

3.4 X-ray diffraction (XRD)

XRD is used to determine the crystalline structure of nanoparticles. By analysing the diffraction patterns, researchers can obtain information about the phase and crystallinity of the nanoparticles, which can affect their stability and reactivity (10).

4. Applications of green-synthesised nanoparticles

The biogenic synthesis of nanoparticles has a broad range of applications across various industries, particularly in the fields of medicine, agriculture, and environmental remediation.

4.1 Medical applications

Green-synthesised nanoparticles are being explored for drug delivery, cancer therapy, and diagnostic imaging. Due to their biocompatibility, these nanoparticles can deliver drugs directly to targeted cells, minimising side effects. For instance, gold nanoparticles synthesised using plant extracts have shown promise in drug delivery systems due to their ease of functionalization and stability (11). Silver nanoparticles, known for their antimicrobial properties, are also used in wound healing and infection control (12).

4.2 Environmental remediation

Green nanoparticles have been successfully applied in the removal of heavy metals and organic pollutants from wastewater. Their high surface area and reactivity make them ideal for adsorption and catalytic degradation of toxic substances (13). Fungal-based nanoparticles, in particular, have shown excellent potential in removing contaminants from the environment due to their unique surface properties and interaction with pollutants.

4.3 Agricultural applications

In agriculture, biogenic nanoparticles are used to improve crop yield, protect plants from diseases, and enhance the effectiveness of pesticides. They have also been used as nano-fertilisers to enhance nutrient uptake in plants (14). Additionally, biogenic nanoparticles are utilised in the formulation of environmentally friendly pesticides with reduced toxicity to non-target organisms.

4.4 Aquaculture applications

Green-synthesised nanoparticles are increasingly being explored in aquaculture to improve water quality, enhance the growth of aquatic organisms, and control diseases.

Nanoparticles, particularly those derived from plants and microorganisms, are being utilised to remove toxins from aquaculture systems, such as heavy metals and organic pollutants. Furthermore, antimicrobial nanoparticles can help control bacterial and fungal infections in fish, promoting healthier aquatic life. Silver nanoparticles, in particular, are widely used for their bactericidal and antifungal properties in aquaculture (15). Additionally, biogenic nanoparticles are being studied for their ability to enhance the growth and disease resistance of fish and shrimp, improving overall aquaculture productivity (16).

4.5 Energy

Biogenically synthesised nanoparticles are used in renewable energy technologies, such as solar cells and hydrogen production, due to their superior electrical and catalytic properties (17).

5. Challenges and limitations of biogenic synthesis

Despite the promising potential of biogenic nanoparticles, several challenges and limitations must be addressed:

5.1 Scalability

The synthesis of nanoparticles at an industrial scale remains a significant challenge. Although laboratory-scale synthesis has been demonstrated, scaling up the production process while maintaining consistency in nanoparticle size, shape, and stability is still a hurdle (18).

5.2 Standardisation

There is a lack of standardised protocols for the synthesis and characterisation of biogenic nanoparticles, which makes it difficult to compare results across studies. Further research is needed to establish standardised guidelines for nanoparticle production (19).

5.3 Environmental impact

While biogenic synthesis is considered more environmentally friendly than chemical methods, the long-term environmental impact of using biological systems for nanoparticle production needs further investigation. The possibility of unintended ecological consequences, such as toxicity to beneficial microorganisms, must be considered (20).

6. Future prospects and research directions

The future of green nanotechnology is promising, with increasing interest in biogenic synthesis methods. Research should focus on improving the scalability and reproducibility of biogenic nanoparticle synthesis. Additionally, there is a need for greater exploration of the diverse biological sources available for nanoparticle production. Innovations in enzyme and biomolecule-mediated synthesis could lead to more precise control over nanoparticle properties, opening up new avenues for medical and industrial applications.

Further studies should also focus on assessing the long-term safety and environmental impacts of biogenic nanoparticles, especially in large-scale applications. Collaborative efforts between researchers, policymakers, and industry stakeholders will be key to realising the full potential of green nanotechnology.

7. Conclusion

Green nanotechnology, particularly the biogenic synthesis of nanoparticles, has emerged as a sustainable and eco-friendly alternative to traditional chemical methods. With applications spanning across medicine, agriculture, and environmental remediation, biogenic nanoparticles offer tremendous promise for addressing some of the world's most pressing challenges. However, to unlock their full potential, further research is needed to address the challenges associated with scalability, standardisation, and environmental impact. As the field continues to evolve, the integration of biogenic nanoparticles into real-world applications will play a crucial role in advancing the principles of sustainability and environmental stewardship.

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