

Green Synthesized Monometallic And Bimetallic Nanoparticles: A Sustainable Approach To Controlled Drug Delivery

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Abstract

The growing demand for sustainable and biocompatible nanomaterials has driven significant interest in green synthesis approaches for nanoparticle production. Green synthesized monometallic and bimetallic nanoparticles have emerged as promising candidates in nanomedicine, particularly for controlled drug delivery systems. This study provides a comprehensive analysis of biological synthesis routes, physicochemical characteristics, and therapeutic applications of these nanoparticles. Green synthesis utilizes plant extracts, microorganisms, and biomolecules as reducing and stabilizing agents, minimizing environmental toxicity and enhancing biocompatibility (jahangirian et al., 2017; singh, 2023). Monometallic nanoparticles offer simplicity and well-defined properties, while bimetallic nanoparticles exhibit synergistic effects that improve drug loading efficiency and targeting capability (morgan, 2024). The paper further explores drug delivery mechanisms, including passive and active targeting, stimuli-responsive release, and pharmacokinetic improvements. Despite advancements, challenges such as scalability, reproducibility, and regulatory approval remain critical barriers. Future perspectives emphasize integration with artificial intelligence and personalized medicine. This review highlights the potential of green nanotechnology in revolutionizing sustainable drug delivery systems.

Keywords: Green Synthesis, Nanoparticles, Drug Delivery, Monometallic, Bimetallic, Sustainable Nanomedicine.

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1. Introduction

Nanotechnology has transformed modern biomedical science by enabling precise manipulation of materials at the nanoscale, leading to innovative applications in drug delivery, diagnostics, and therapeutics. Nanoparticles, typically ranging from 1 to 100 nm, exhibit unique properties such as high surface area-to-volume ratio, tunable optical characteristics, and enhanced chemical reactivity, which significantly improve drug delivery efficiency (Ying, 2022).

Traditional drug delivery systems often suffer from limitations such as poor solubility, low bioavailability, rapid degradation, and non-specific targeting. These limitations can result in reduced therapeutic efficacy and increased side effects. Nanoparticle-based drug delivery systems address these challenges by enabling controlled release, targeted delivery, and improved pharmacokinetics (Khafaga, 2023).

However, conventional nanoparticle synthesis methods rely heavily on chemical and physical techniques

involving hazardous solvents, high temperatures, and energy-intensive processes. These approaches raise serious concerns regarding environmental sustainability and biological safety (Samuel, 2022).

Green synthesis has emerged as a viable alternative, employing biological entities such as plant extracts, bacteria, fungi, and algae to produce nanoparticles in an eco-friendly manner. These biological systems contain natural reducing and stabilizing agents, eliminating the need for toxic chemicals while enhancing biocompatibility (Mukherjee, 2021).

The integration of green chemistry principles into nanotechnology has led to the development of "green nanomedicine," which focuses on sustainable and safe nanoparticle production for biomedical applications. Within this framework, monometallic and bimetallic nanoparticles have gained significant attention due to their versatile properties and therapeutic potential (Morgan, 2024).

Green Synthesized Monometallic and Bimetallic Nanoparticles: A Sustainable Approach to Controlled Drug Delivery

This paper aims to provide a detailed understanding of green synthesized nanoparticles and their role in controlled drug delivery, with a comparative analysis of monometallic and bimetallic systems.

2. Green Synthesis of Nanoparticles

2.1 Concept and Principles

Green synthesis is grounded in the principles of green chemistry, which emphasize the reduction of hazardous substances, energy efficiency, and the use of renewable resources. In nanoparticle synthesis, biological molecules such as proteins, enzymes, polysaccharides, and phytochemicals act as reducing agents that convert metal ions into nanoparticles (Singh, 2023).

Unlike conventional methods, green synthesis operates under mild conditions, such as ambient temperature and pressure, making it energy-efficient and environmentally benign. Furthermore, the presence of natural capping agents enhances nanoparticle stability and prevents aggregation (Samuel, 2022).

2.2 Biological Sources and Their Role

Green synthesis utilizes diverse biological sources, each contributing unique biochemical properties:

- **Plant Extracts:** Rich in flavonoids, alkaloids, terpenoids, and phenolic compounds, which act as reducing and stabilizing agents.
- **Microorganisms:** Bacteria and fungi produce enzymes that facilitate nanoparticle formation.
- **Algae:** Provide polysaccharides and proteins for nanoparticle synthesis.

Plant-mediated synthesis is particularly advantageous due to its simplicity, scalability, and rapid reaction rates (Mukherjee, 2021).

2.3 Mechanism of Green Synthesis

The synthesis process typically involves three stages:

1. **Reduction:** Metal ions (e.g., Ag^+ , Au^{3+}) are reduced to their metallic state by phytochemicals.
2. **Nucleation:** Formation of small clusters of atoms.
3. **Growth and Stabilization:** Nanoparticles grow and are stabilized by biomolecules acting as capping agents.

The size and morphology of nanoparticles depend on factors such as pH, temperature, and concentration of biological extracts (Singh, 2023; Morgan, 2024).

3. Monometallic Nanoparticles

Monometallic nanoparticles consist of a single type of metal and are widely studied due to their well-defined properties and ease of synthesis.

3.1 Types and Properties

Common monometallic nanoparticles include:

- Silver (Ag)
- Gold (Au)

Copper (Cu)

Iron (Fe)

These nanoparticles exhibit remarkable properties such as antimicrobial activity, optical tunability, and catalytic efficiency. Their high surface area enhances drug adsorption and interaction with biological systems (Kaushik, 2022).

3.2 Role in Drug Delivery

Monometallic nanoparticles play a critical role in drug delivery systems by:

- Enhancing drug solubility
- Protecting drugs from degradation
- Enabling targeted delivery

Gold nanoparticles, for instance, are extensively used in cancer therapy due to their ability to bind with ligands and target tumor cells. Similarly, silver nanoparticles are widely used for antimicrobial drug delivery (Khafaga, 2023).

3.3 Limitations

Despite their advantages, monometallic nanoparticles have limitations such as:

- Limited functional diversity
- Lower stability compared to bimetallic systems
- Reduced efficiency in complex therapeutic applications

4. Bimetallic Nanoparticles

Bimetallic nanoparticles consist of two different metals, offering enhanced physicochemical and biological properties.

4.1 Structural Configurations

Bimetallic nanoparticles can exist in various forms:

- Alloyed structures
- Core-shell structures
- Segregated or heterostructured forms

These structures influence their catalytic activity, stability, and drug delivery efficiency (Morgan, 2024).

4.2 Advantages in Drug Delivery

Bimetallic nanoparticles exhibit several advantages over monometallic systems:

- Synergistic interactions between metals
 - Enhanced drug loading capacity
 - Improved targeting and controlled release
 - Higher stability and resistance to degradation
- These features make them highly suitable for advanced therapeutic applications such as cancer treatment and gene delivery (Saxena, 2025).

4.3 Applications

Bimetallic nanoparticles are used in:

- Targeted cancer therapy

Green Synthesized Monometallic and Bimetallic Nanoparticles: A Sustainable Approach to Controlled Drug Delivery

- Photothermal therapy
 - Controlled drug release systems
- Their multifunctionality allows simultaneous diagnosis and treatment, known as theranostics.

5. Nanoparticle-Based Drug Delivery Systems

5.1 Mechanisms of Drug Delivery

Nanoparticles facilitate drug delivery through multiple mechanisms:

- **Passive Targeting:** Utilizes enhanced permeability and retention (EPR) effect in tumor tissues.
- **Active Targeting:** Involves ligand-receptor interactions for specific targeting.
- **Stimuli-Responsive Release:** Triggered by pH, temperature, or enzymes.

These mechanisms significantly improve therapeutic efficiency and reduce systemic toxicity (Khafaga, 2023).

5.2 Pharmacokinetic Advantages

Nanoparticles improve:

- Drug absorption
 - Circulation time
 - Controlled release profiles
- This leads to better therapeutic outcomes and reduced dosing frequency (Kaushik, 2022).

6. Comparative Analysis

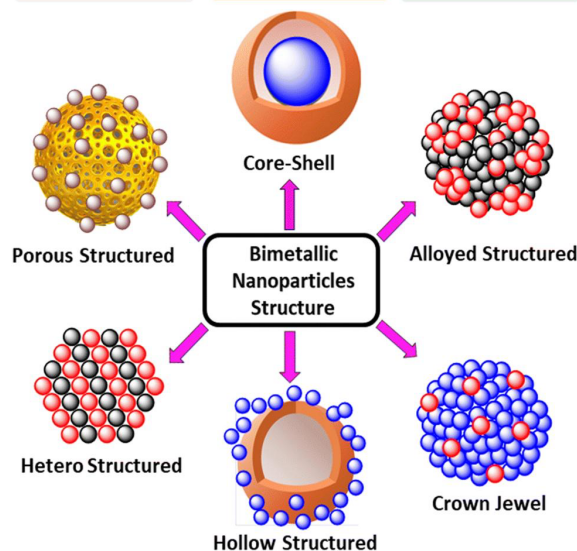
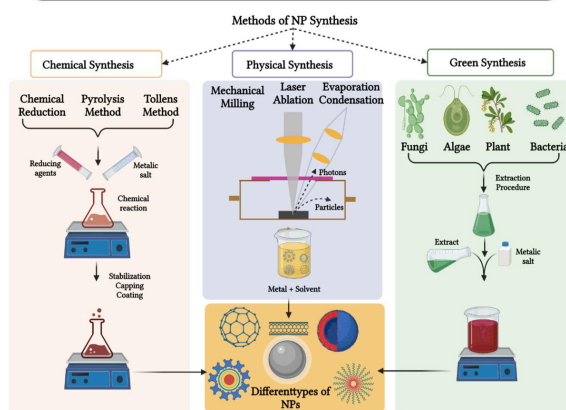
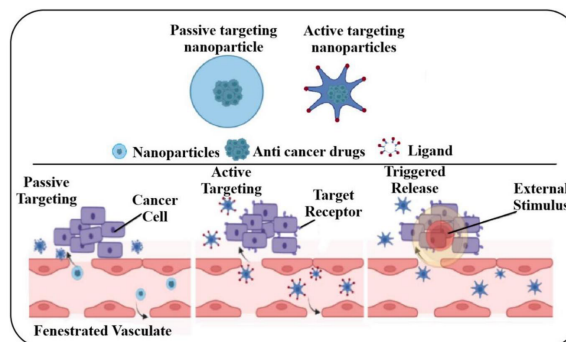
Feature	Monometallic	Bimetallic
Complexity	Low	High
Stability	Moderate	High
Drug loading	Moderate	High
Efficiency	Good	Superior
Applications	Basic therapies	Advanced therapies

7. Characterization Techniques

Accurate characterization is essential for ensuring nanoparticle quality and performance. Techniques include:

- **UV-Vis Spectroscopy:** Confirms nanoparticle formation
 - **FTIR:** Identifies functional groups
 - **SEM/TEM:** Determines morphology and size
 - **XRD:** Analyzes crystalline structure
- These techniques provide insights into nanoparticle behavior in biological systems (Ijaz, 2020).

8. Mechanism Illustration



9. Challenges and Limitations

Despite promising advancements, several challenges hinder widespread application:

- Lack of reproducibility due to biological variability
 - Difficulty in scaling up production
 - Limited understanding of long-term toxicity
 - Regulatory challenges for clinical approval
- Addressing these challenges is essential for commercialization and clinical translation (Samuel, 2022; Saxena, 2025).

10. Future Perspectives

Future research directions include:

Green Synthesized Monometallic and Bimetallic Nanoparticles: A Sustainable Approach to Controlled Drug Delivery

- Integration of artificial intelligence in nanoparticle design
 - Development of hybrid and multifunctional nanoparticles
 - Clinical trials and regulatory frameworks
 - Personalized nanomedicine
- Green nanotechnology is expected to play a crucial role in sustainable healthcare systems (Morgan, 2024).

11. Conclusion

Green synthesized monometallic and bimetallic nanoparticles represent a sustainable and efficient approach to controlled drug delivery. Their eco-friendly synthesis, enhanced biocompatibility, and superior functional properties make them highly promising for biomedical applications. While challenges remain, continued research and technological advancements are expected to drive their successful integration into clinical practice (Khafaga, 2023).

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