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Review article

GREEN SYNTHESIS OF METAL NANOPARTICLES USING PLANT EXTRACTS AND THEIR APPLICATION IN PHARMACEUTICAL NANOTECHNOLOGY

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Abstract

This paper explores the synthesis, characteristics, and pharmaceutical applications of metal nanoparticles, with particular focus on eco-friendly "green synthesis" methods utilizing plant-derived extracts. Nanotechnology, a concept first proposed by Nobel Laureate Richard Feynman, has rapidly evolved as a multidisciplinary field with significant implications in pharmacy, medicine, and environmental sciences. Nanomaterials, with dimensions ranging from 1 to 100 nanometers, exhibit unique physicochemical, optical, and electrical properties that enhance drug bioavailability, targeting, and therapeutic efficiency.
Various types of nanoparticles are discussed, including noble metal-based (Au, Ag, Pt), bimetallic, oxide, sulfide, and carbon-based forms. Green synthesis is emphasized as a sustainable and non-toxic approach, involving the reduction of metal ions by plant secondary metabolites such as polyphenols and terpenes. This method not only reduces energy consumption and hazardous waste, but also results in stable nanoparticles with potential antioxidant and antimicrobial activities, aligning with pharmaceutical safety and efficacy standards.
Moreover, the study reviews the integration of green-synthesized metal nanoparticles into voltammetric biosensors, demonstrating improved electrochemical sensitivity and selectivity for bioanalytical applications. These findings underline the potential of green nanotechnology in pharmaceutical analysis, drug delivery systems, and diagnostics.
In conclusion, green synthesis of nanoparticles presents a promising strategy for the development of advanced pharmaceutical technologies, offering a safer, more sustainable alternative for nanoparticle production with broad clinical and industrial relevance.

Keywords: nanoparticles, green synthesis, metal nanoparticles, plant extracts, voltammetric sensors, pharmaceutical application, nanotechnology, bioreduction, electrochemistry, sustainable technologies.

1. Introduction

Nanotechnology represents the application of science for the control of materials at the molecular level [1]. The concept of nanotechnology, as initially formulated by Richard Feynman, introduced revolutionary changes across scientific and industrial disciplines.
Nanoparticles are defined as three-dimensional materials with external dimensions ranging from 1 to 100 nanometers [1]. This nanometric domain enables the emergence of new properties that are fundamentally different from those at the macroscopic scale, owing to the increased specific surface area and the presence of free electronic bonding. The advantages of nanoparticles over bulk materials manifest in their mechanical, biological, catalytic, thermal, electrical, and optical properties. Their extremely compact surface allows for significant surface functionalization within a limited volume, thereby enhancing their reactivity and biofunctionality [2]. This morphological characteristic, along with the high surface-to-mass ratio compared to bulk materials, leads to substantial changes in the energetic state of surface atoms and consequently to the transformation of their physicochemical properties [3].
When used in larger quantities, the dominant presence of surface atoms in nanoparticles results in higher surface energy, which directly correlates with their improved catalytic activity. These

features position nanoparticles as superior candidates for application in various catalytic processes [4–6].
The physical and chemical synthesis of nanoparticles has been known for a long time; however, recent advances highlight the pivotal role of microorganisms and biological systems in nanoparticle synthesis.
In recent years, there has been a growing trend in the use of nanoparticles synthesized through environmentally friendly methods—the so-called green synthesis. The biological synthesis of metallic nanoparticles using plants is increasingly being explored as an effective and safe alternative to chemical and physical methods. This approach is more cost-effective and suitable for large-scale nanoparticle synthesis. Plant extracts act simultaneously as reducing agents and as capping ligands. The involvement of biomolecules such as enzymes, proteins, amino acids, vitamins, polysaccharides, and organic acids contributes to bioreduction that is environmentally safer and offers significant economic and technological benefits, such as lower energy consumption, reduced potential for toxic waste generation, and straightforward laboratory implementation [7]. The primary goal of these eco-friendly methods is to direct the transition of nanoparticles from laboratory-scale research to practical commercial applications, while ensuring cost-effective production.

2. Green Synthesis of Nanoparticles

Within the framework of green synthesis of nanoparticles, biogenic materials of plant origin—such as roots, peels, leaves, flowers, fruits, and seeds—are considered valuable bioresources capable of acting as reducing and stabilizing agents in the formation of nanostructures. In addition to plant-derived materials, green synthesis also includes other biological systems, such as microorganisms (e.g., bacteria, fungi, and algae), as well as natural products like honey and starch, which serve as environmentally friendly alternatives to conventional chemical reagents. These green biomaterials, due to their natural content of biologically active compounds such as polyphenols, play a key role in the reduction of metal ions to their elemental (zero-valent) state [8]. The reduction process occurs through complex biochemical interactions between phytochemicals and metal precursors, enabling controlled nucleation and growth of nanoparticles. Under optimized conditions—such as appropriate temperature, concentration gradients, pH levels, and the presence of ambient oxygen—stable metallic nanoparticles with homogeneous morphological and structural characteristics can be efficiently synthesized.
One of the main advantages of this bioinspired approach to synthesis is the reduction or complete avoidance of nanoparticle aggregation, which represents one of the major challenges in conventional nanoparticle synthesis methods [9]. Aggregation, i.e., the joining of individual nanoparticles into aggregates or clusters, typically occurs after a certain period following their formation and depends on multiple factors, including the concentration of the particles, their chemical nature, temperature conditions, and the presence of solvents such as alcohols, which are commonly used in traditional synthetic protocols. The green approach, through the natural stabilizing ability of biomolecules, allows for better dispersion and long-term stability of the synthesized nanoparticles, thereby significantly improving their applicability in various technological and biomedical fields.

3. Voltammetric Biosensors Based on Green Metallic Nanoparticles

Contemporary scientific literature extensively documents that numerous nanoparticles, particularly those based on metals and graphene nanostructures, exhibit outstanding catalytic properties that surpass the performance of traditional catalysts. These nanostructured materials, owing to their high specific surface area, quantum effects, and large number of active surface sites, are characterized by exceptional electrochemical reactivity and selectivity[10].

Within the field of electrochemical detection, one of the most important strategies for enhancing the sensitivity and efficiency of sensor platforms is the functionalization of the working electrode with nanoparticles possessing pronounced catalytic attributes. This is most commonly achieved through a process of spontaneous self-assembly, wherein the working electrode is immersed in a colloidal or supramolecular solution containing nanoparticles, allowing them to adsorb or bind to the electrode surface over a defined period [11]. This process, which may involve physisorption, chemisorption, or electrostatic interactions, results in the formation of a nanostructured electrode surface with increased active area and modified electrocatalytic properties.

Voltammetric (bio)sensors with such nanoparticle-based modification of the working electrode demonstrate significant analytical potential. Primarily, they can markedly reduce the overpotential required to initiate specific electrochemical reactions, leading to improved energy efficiency of the system [12]. Additionally, these modified surfaces often facilitate electron transfer, which may enable the reversibility of redox reactions that are typically considered irreversible when studied using unmodified electrodes. This effect is particularly important in the context of analytical and biosensing applications, where sensor selectivity, sensitivity, and temporal stability are of critical importance [13-14].

In summary, the integration of metallic and carbon-based nanoparticles into the architecture of electrode surfaces represents a powerful tool for advancing the performance of electrochemical sensors, thereby opening new opportunities for their application in biomedical diagnostics, environmental monitoring, and next-generation chemical sensing technologies.

Conclusion

Green chemistry, as a contemporary scientific paradigm, represents a progressive discipline whose primary aim is to redefine chemical processes through the implementation of principles that minimize the use and generation of toxic, hazardous, or otherwise harmful substances to human health and the environment. Over the past two decades, significant progress has been made in adapting these principles as a sustainable alternative to conventional methods, which often involve expensive, energy-inefficient, and environmentally damaging procedures.

Within this ecological orientation, green synthesis of nanomaterials has emerged as one of the most promising solutions for the sustainable development of nanotechnology. The application of biogenic reducing agents and environmentally friendly synthesis protocols enables not only the production of functional nanoparticles with high stability and catalytic activity but also a substantial reduction in the risks associated with their toxicity and environmental footprint. In this context, particular emphasis is placed on the green synthesis of metallic nanoparticles using natural sources such as plant extracts, microorganisms, and biopolymers.

Over the past 15 years, green nanomaterials have gained increasing importance in the design of advanced voltammetric sensors, especially in the fields of biosensing, microbiological diagnostics, and the quantitative analysis of biologically and environmentally relevant analytes. These devices exhibit high sensitivity, selectivity, and durability, making them attractive tools for future applications in medical diagnostics, pollution and food monitoring, and industrial

process control. However, despite their analytical potential, most of these sensors remain at the laboratory evaluation stage, and broad commercial implementation is still lacking.
Given the limited availability of commercially validated voltammetric sensors based on green nanomaterials, comprehensive and standardized validation studies are required to ensure their practical applicability under real-world conditions [15]. Future research efforts should focus on improving the reproducibility, stability, and economic feasibility of these systems.
In a broader context, it can be anticipated that electrochemical sensors based on green nanotechnology represent a realistic and sustainable alternative to costly and complex instrumental methods. Their potential integration into portable, low-cost, and environmentally friendly analytical devices may significantly contribute to the democratization of diagnostic technologies and improve access to modern analytical solutions across various fields—from clinical practice to industrial processes and environmental monitoring.

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