CATALYTIC POTENTIAL OF ENVIRONMENTALLY-FRIENDLY METAL NANOPARTICLES SYNTHESIZED THROUGH SUSTAINABLE METHODS: REVIEW

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Abstract:

Nanotechnology is a rapidly advancing field with extensive applications spanning across disciplines, including science, engineering, healthcare, and pharmaceuticals. Within the myriad of techniques employed for nanoparticle production, the utilization of green technologies stands out as a straightforward and environmentally friendly approach. Nanoparticles synthesized from plant extracts have gained significant prominence in recent decades due to their multitude of advantages, such as cost-effectiveness, product stability, and eco-friendly processes.

The accessibility and versatility of plant-derived nanoparticles have fostered research into their synthesis, with a growing interest in employing alternative sources, including bacteria, fungi, algae, proteins, enzymes, and more. These resources offer the prospect of large-scale nanoparticle production with minimal environmental impact. Nevertheless, nanoparticles originating from plant extracts and phytochemicals exhibit superior reduction and stabilization properties, underpinning their diverse range of attributes. These attributes encompass catalyst and photocatalyst capabilities, magnetic properties, antibacterial effects, cytotoxicity, binding to circulating tumor deoxyribonucleic acid (CT-DNA), gas sensing, and more.

In the contemporary context, nanoparticles have a pivotal role to play in wastewater treatment, rendering it suitable for various applications. Nano-sized photocatalysts, in particular, hold significant promise for the elimination of substantial pollutants, including organic dyes, heavy metals, and pesticides, from industrial effluents in an eco-friendly and sustainable manner.

In light of these developments, this review article delves into the synthesis of diverse metal nanoparticles utilizing various plant extracts. It also explores the comprehensive characterization of these nanoparticles using techniques such as UV-Vis spectroscopy (ultraviolet-visible), X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FTIR), and more. Furthermore, the review provides insights into the catalytic activities of these nanoparticles in addressing a range of hazardous scenarios.

1. Introduction:

Access to clean water is a fundamental prerequisite for human health and survival. However, many regions worldwide are grappling with a dire shortage of potable water. This crisis stems not only from escalating population densities but is exacerbated by the expansion of numerous industrial sectors, including textiles, automobiles, petrochemicals, electronics, food, and pharmaceuticals. The byproducts of these industries, notably wastewater, have become a pressing environmental concern. In several developing nations, the industrial sector alone accounts for approximately 22% of global water usage, and over 70% of this consumption results in untreated industrial wastewater, a significant portion of which comprises pollutants. Among these contaminants, dyes, prevalent in industries such as textiles, food, and pharmaceuticals, pose a substantial threat to aquatic ecosystems and the surrounding environment. These effluents are pernicious due to their toxicity, vivid coloration, elevated chemical oxygen demand (COD), and low biodegradability.

To mitigate the ecological hazards posed by these noxious compounds, researchers have been exploring cost-effective degradation techniques, notably photocatalysis, which has gained substantial traction over the past two decades for the decomposition of dyes in wastewater and effluents.

Nanoparticles (NPs), materials with distinct properties compared to their bulk and molecular counterparts, are considered the cornerstone of nanotechnology. NPs, with at least one dimension below 100 nanometers, have garnered immense attention due to their versatile applications across various domains, encompassing traditional chemistry, medicine, and environmental technologies. These NPs, characterized by their high surface area-to-volume ratio and unique surface properties, have been harnessed by industries and researchers for millennia. The renewed interest in NPs can be attributed to the capacity for large-scale synthesis and precise characterization, enabling the manipulation of their properties, including atomic structure, electronic and magnetic attributes, and physical and chemical behaviors, relative to bulk materials.

Nanoparticles can exist in various dimensions, from zero-dimensional nano dots to one-dimensional structures like graphene, two-dimensional materials such as carbon nanotubes, and three-dimensional entities like gold NPs. Their distinct functional attributes render NPs invaluable for a myriad of applications, including photocatalysis, catalysis, sensor technology, magnetic properties, DNA binding, and applications in food, engineering, medicine, disease diagnosis and treatment, anti-carcinogenic, antioxidant, anti-tubercular, and antimicrobial domains.

In the context of wastewater treatment, the presence of organic contaminants necessitates their elimination or degradation before the effluents are released into the environment, where they can affect both groundwater and surface water quality. This concern has spurred the development of innovative treatment methods, with photocatalysis gaining particular prominence in pollutant degradation. An ideal photocatalyst should be stable, cost-effective, non-toxic, and highly photoactive.

This review aims to address the current gaps in literature regarding the photocatalytic activity of metal NPs synthesized using plant extracts. It offers insights into the development of novel, efficient, and cost-effective NPs for the treatment of dye-contaminated wastewater through photocatalysis.

Why the Green Approach for NPs Synthesis?

Nanoparticles can be synthesized through two primary methods: the "top-down" approach, which involves reducing bulk materials to nanoparticles through methods like grinding or milling, and the "bottom-up" approach, which synthesizes nanoparticles through physical, chemical, and biological methods. While physical and chemical methods offer several routes for nanoparticle synthesis, they often involve high temperatures and pressures and may employ toxic substances, raising environmental and safety concerns.

In this context, green synthesis represents a subset of green chemistry, striving to create safer chemical products and processes that minimize or eliminate the use of hazardous elements. Green synthesis of nanomaterials serves two primary objectives: first, it aims to develop nanomaterials that can effectively combat environmental pollutants and integrate nanomaterials into environmental technologies to remediate contaminated environments. Second, it strives to reduce harm to human health and the environment resulting from human activities.

The biological approach to nanoparticle synthesis aligns with green chemistry principles, as it avoids toxic substances, is environmentally friendly, and energy-efficient. Biological synthesis of nanoparticles leverages sources such as fungi, bacteria, plants, and animals. Among these sources, plant extracts offer distinct advantages, including cost-effectiveness and feasibility. Plants are rich in a variety of phytochemicals, including proteins, carbohydrates, enzymes, phenolic acids, and alkaloids, which can play essential roles in reducing and stabilizing nanoparticles. This makes plant extracts a preferred choice, significantly reducing the need for chemical reducing, capping, and stabilizing agents during nanoparticle synthesis.

2. Synthesis and Characterization of NPs:

Plant Extract Preparation

The process of preparing plant extracts is a critical phase in nanoparticle synthesis. It commences with the careful collection of leaves from herbal plants, which is carried out under the guidance of a subject expert who identifies the specific plants of interest. The freshly harvested leaves undergo a meticulous cleaning procedure, involving rinsing with running water and double distilled water (DDW). Subsequently, the cleaned leaves are finely chopped and left to dry naturally in the shade or under the sun.

For the extraction itself, a predetermined quantity of powdered leaves, usually ranging from 5 to 10 grams, is immersed in a known volume of double distilled water (100 mL). This mixture is then incubated at a temperature range of 40 to 50°C for a duration of 80 to 100 minutes. Following incubation, the leaf extract is allowed to cool to ambient temperature before being meticulously filtered using Whatman (No. 41) filter paper.

Phytochemical Tests

The plant kingdom is a vast repository of natural compounds, many of which remain to be fully explored for their potential health benefits. Plants are a rich source of essential phytochemicals known for their therapeutic and medicinal properties.

These phytochemicals play a pivotal role in the medicinal properties of various plants and serve as the foundation for combatting various ailments. Their broad spectrum of activities contributes to bolstering the immune system and conferring long-term disease resistance, protecting the body against harmful pathogens.

Phytochemical tests represent a crucial aspect of nanoparticle synthesis from plant extracts, shedding light on the chemical composition of these extracts. To ensure the accuracy of these tests, they are conducted in accordance with standard protocols. A variety of phytochemical tests are employed, as outlined in Table 1, to determine the presence or absence of specific phytochemical constituents within the plant extracts. These tests are essential for the comprehensive investigation of the constituents present in the extracts.

Characterization:

The bedrock of any scientific research endeavor lies in the thorough characterization of the samples under investigation. In the context of nanoparticle synthesis, it is instrumental characterization that provides vital insights into the formation of nanoparticles, including their size, morphology, and surface area. Several techniques are employed to achieve this, such as Fourier-transform infrared spectroscopy (FTIR), UV-visible spectroscopy (UV-Vis), scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy-dispersive X-ray analysis (EDX), and X-ray diffraction (XRD).

FTIR and UV-Vis Spectroscopy serve as instrumental pillars in the characterization process. UV-Vis spectroscopy enables the confirmation of nanoparticle formation by comparing the peaks observed in the spectra of metal salt and leaf extract. FTIR, on the other hand, helps elucidate valuable information regarding chemical bonds and functional groups present in the nanoparticles.

XRD Analysis is instrumental in unveiling the crystal parameters, structural attributes, and size of the nanoparticles. This technique provides a window into the crystalline nature of the synthesized materials.

SEM Analysis delves into the surface morphology and size of the nanoparticles, offering a visual perspective of their physical characteristics.

TEM takes characterization to a more granular level, enabling precise measurement of the nanoparticles' size. This technique offers detailed insights into the individual particles' dimensions.

EDX analysis provides a quantitative understanding of the elemental composition of the nanoparticles, revealing the percentage of elements present in the sample.

In the realm of nanoparticle characterization, these techniques, including UV-Vis spectroscopy, FTIR spectroscopy, TEM, and SEM, represent a few of the commonly employed methods that play a pivotal role in unraveling the properties and attributes of the synthesized nanoparticles.

3. Conclusions:

Green synthesis technology represents an eco-conscious, non-toxic, and environmentally sound approach to crafting metal nanoparticles, and its burgeoning commercial prospects and feasibility render it of significant interest. This review is dedicated to chronicling the fabrication of diverse metal nanoparticles derived from an array of plant extracts. These nanoparticles are meticulously characterized through techniques such as UV-Vis spectroscopy, X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FT-IR), scanning electron microscopy (SEM), and transmission electron microscopy (TEM).

A pivotal factor for effective photocatalytic activity is the optical band value, which should be below 5 eV. Metal nanoparticles obtained from plant extracts demonstrate highly efficient pollutant organic dye degradation capabilities and water purification functionalities. Recent advancements in metallic nanoparticle research have illuminated the promising prospects of amalgamating metallic nanoparticles with semiconductors, particularly in the realm of visible light-responsive materials. Identifying and addressing the challenges that surface in this sphere promises accelerated progress, thereby positioning metallic nanoparticles as pivotal elements in visible light photocatalysis.

The photocatalytic prowess of these environmentally friendly photocatalysts is indeed commendable. Nonetheless, their stability and user-friendliness remain areas in need of enhancement. Ensuring the sustained photocatalytic efficiency of these materials mandates the continual introduction of scavengers. The limited industrial application of green synthetic photocatalysts can be ascribed to factors such as low nanoparticle yields, the need for laboratory-scale setups, and insufficient recycling capacities.

Consequently, there is a pressing need to refine protocols, making them more cost-effective and competitive with conventional methods for large-scale nanoparticle production. The advancement of dependable and eco-friendly processes for metallic nanoparticle synthesis represents a significant stride in applied nanotechnology. It is our aspiration that this review will serve as a valuable resource for nascent researchers, offering insights into the cleaner production of metal nanoparticles and their versatile applications.

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