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A Summary of Recent Developments in the Botanical Biosynthesis of Nanoparticles for Catalytic, Water Treatment, and Agricultural Application

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Abstract

Nanotechnology has emerged as a promising field for various applications, including catalysis, water treatment, and agriculture. The synthesis of nanoparticles using botanical sources has gained significant attention due to its eco-friendly and sustainable nature. This review article provides a comprehensive overview of recent developments in the botanical biosynthesis of nanoparticles and their applications in catalysis, water treatment, and agriculture. It discusses various plant-based materials, such as extracts, biomolecules, and phytochemicals that have been utilized for nanoparticle synthesis. The review also highlights the characterization techniques employed to analyse the physicochemical properties of the synthesized nanoparticles. Furthermore, it explores the catalytic, water treatment, and agricultural applications of these nanoparticles, including their potential mechanisms and performance in relevant systems. Finally, the challenges and future prospects of botanical biosynthesis for nanoparticle applications are discussed, emphasizing the need for further research and development in this rapidly evolving field.

Keywords: Nanotechnology; Waste water treatment; Biosynthesis; Agriculture

Introduction

Nanotechnology, the science and engineering of materials at the nanoscale, has garnered significant attention due to its potential to revolutionize various industries. At the nanoscale, materials exhibit unique properties and behaviors, offering novel opportunities for innovation and advancement. Nanoparticles, which are particles with dimensions ranging from 1 to 100 nanometers, have emerged as key building blocks in nanotechnology, finding applications in diverse fields such as electronics, medicine, energy, and environmental science. The applications of nanoparticles are vast and encompass areas such as catalysis, water treatment, and agriculture. In catalysis, nanoparticles provide enhanced surface area and unique surface properties, allowing for efficient and selective reactions. They are utilized as catalysts in chemical transformations, enabling improved reaction rates, selectivity, and overall process efficiency. The use of nanoparticles as catalysts has the potential to revolutionize industrial processes and contribute to sustainable development.

Water treatment is another critical area where nanoparticles have demonstrated their utility. Nanoparticles can be employed for the removal of contaminants, including heavy metals, organic pollutants, and pathogens, from water sources. Their high surface area and reactivity enable effective adsorption, degradation, and disinfection processes, leading to the purification of water resources. The development of efficient and environmentally friendly water treatment methods is crucial for addressing global water scarcity and ensuring access to safe drinking water. In agriculture, nanoparticles offer promising opportunities to improve crop productivity, disease management, and environmental sustainability. They can be used for targeted delivery of nutrients and agrochemicals to plants, enhancing nutrient uptake and minimizing waste. Additionally, nanoparticles possess antimicrobial properties that can aid in controlling plant diseases caused by bacteria, fungi, and viruses. By integrating nanotechnology into agriculture, it is possible to develop sustainable farming practices that reduce resource consumption and minimize environmental impact.

While the applications of nanoparticles are vast, their synthesis often involves the use of hazardous chemicals and energy-intensive processes, raising concerns regarding environmental impact and sustainability. In this context, botanical biosynthesis of nanoparticles has gained considerable attention as an alternative approach. Botanical biosynthesis harnesses the natural reducing and stabilizing capabilities of plant-based materials, such as extracts, biomolecules, and phytochemicals, to synthesize nanoparticles. This green synthesis method offers numerous advantages, including eco-friendliness, cost-effectiveness, and scalability. The importance of botanical biosynthesis in nanoparticle synthesis lies

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in its sustainable nature. By utilizing plant-derived materials, the process reduces the reliance on toxic chemicals, minimizes energy consumption, and contributes to the development of environmentally friendly nanomaterials. Furthermore, botanical biosynthesis provides an opportunity to explore the vast diversity of plant species and their unique properties, potentially leading to the discovery of new nanoparticle synthesis routes and novel nanoparticle properties [1].

Botanical Sources for Nanoparticle Synthesis

Botanical sources offer a wide range of plant-based materials that can be utilized for the biosynthesis of nanoparticles. These materials include plant extracts, which are obtained by extracting bioactive compounds from different parts of plants, as well as specific phytochemicals that play key roles in the formation and stabilization of nanoparticles. Let's explore these botanical sources in more detail:

Plant Extracts and their Constituents

Plant extracts are obtained by extracting bioactive compounds from various parts of plants, such as leaves, stems, flowers, and roots. These extracts are rich in phytochemicals, including phenolic compounds, flavonoids, alkaloids, terpenoids, and proteins, which can act as reducing and stabilizing agents in the synthesis of nanoparticles. The bioactive compounds present in plant extracts serve as reducing agents by donating electrons to metal ions, leading to the reduction and formation of nanoparticles. Additionally, they can also act as stabilizing agents, preventing the agglomeration and ensuring the stability of the synthesized nanoparticles. The composition of plant extracts varies depending on the plant species and the extraction method employed, resulting in different properties and functionalities of the synthesized nanoparticles. Some commonly used plant extracts for nanoparticle synthesis include green tea extract, grape extract, neem extract, aloe vera extract, and turmeric extract. These extracts contain a diverse range of phytochemicals that contribute to the reduction and stabilization of nanoparticles, making them suitable for various applications.

Phytochemicals and their Roles in Nanoparticle Formation

Phytochemicals are specific compounds found naturally in plants, known for their beneficial properties and effects on human health. In the context of nanoparticle synthesis, phytochemicals play crucial roles in the formation, growth, and stabilization of nanoparticles. They exhibit unique chemical properties that enable them to reduce metal ions and control the nucleation and growth of nanoparticles. Certain phytochemicals, such as polyphenols, flavonoids, tannins, saponins, and alkaloids, possess functional groups (e.g., hydroxyl, carboxyl, amine) that facilitate the reduction of metal ions and subsequent nanoparticle formation. The presence of these functional groups enables the phytochemicals to act as reducing and capping agents, controlling the size, shape, and stability of the synthesized nanoparticles. Moreover, phytochemicals exhibit a wide range of biological activities, including antioxidant, antimicrobial, and anti-inflammatory properties. These properties can be imparted to the synthesized nanoparticles, leading to enhanced functionality and potential applications in various fields. Examples of phytochemicals commonly employed in nanoparticle synthesis include quercetin, curcumin, resveratrol, epigallocatechin gallate (EGCG), and berberine. These phytochemicals have shown promise in the biosynthesis of nanoparticles with unique properties and enhanced functionality for different applications.

Biosynthesis of Nanoparticles using Botanical Materials

The biosynthesis of nanoparticles using botanical materials involves the utilization of plant-based extracts, biomolecules, and phytochemicals for the green synthesis of nanoparticles. This section explores the green synthesis approaches and methodologies employed in this process and discusses the factors that influence nanoparticle synthesis [2].

Green Synthesis Approaches and Methodologies

Green synthesis approaches aim to minimize the use of hazardous chemicals, energy consumption, and waste generation in nanoparticle synthesis. When utilizing botanical materials, several green synthesis methodologies have been developed:

Aqueous Extract Method

This method involves the use of plant extracts as reducing and stabilizing agents. The extract is prepared by grinding plant parts in water, followed by filtration or centrifugation to obtain a clear extract. The extract is then mixed with metal precursors, and the reduction reaction occurs under specific conditions, resulting in the formation of nanoparticles.

Microwave-Assisted Method

In this approach, microwave irradiation is used to accelerate the synthesis process. Plant extracts and metal precursors are mixed and exposed to microwave irradiation, leading to rapid reduction and nanoparticle formation. This method offers advantages such as shorter reaction times and enhanced control over the synthesis process.

Hydrothermal Method

The hydrothermal method involves subjecting the plant extract and metal precursors to high-temperature and high-pressure conditions in a sealed reactor. This promotes rapid reaction kinetics and facilitates the formation of nanoparticles. The hydrothermal method is particularly suitable for the synthesis of nanoparticles with controlled sizes and crystallinity.

In-situ Method

In the in-situ method, the synthesis of nanoparticles occurs within the plant tissue or cell cultures. Plant tissues or cells are exposed to metal precursors, and the reduction and nanoparticle formation take place within the plant matrix. This approach offers the advantage of using intact plant systems for nanoparticle synthesis, potentially leading to unique properties and functionalities.

Factors Influencing Nanoparticle Synthesis

Several factors influence the biosynthesis of nanoparticles using botanical materials

Plant Species and Extract Composition

The choice of plant species and the composition of the plant extract significantly impact nanoparticle synthesis. Different plant species contain varying amounts and types of bioactive compounds that act as reducing and stabilizing agents. The phytochemical profile of the plant extract influences the size, shape, and stability of the synthesized nanoparticles [3].

Concentration of Plant Extract and Metal Precursors

The concentrations of the plant extract and metal precursors play a crucial role in nanoparticle synthesis. Optimal concentrations need to be determined to ensure efficient reduction and controlled nanoparticle formation. Deviations from the optimum concentration can result in aggregation, incomplete reduction, or undesired particle sizes.

Reaction Parameters

Various reaction parameters, such as temperature, pH, reaction time, and mixing conditions, affect nanoparticle synthesis. These parameters influence the kinetics of the reduction reaction, nucleation, growth, and stability of nanoparticles. Controlling these parameters is essential to achieve desired nanoparticle properties and functionalities.

Metal Precursors and Stoichiometry

The choice of metal precursors, such as metal salts, determines the composition and properties of the synthesized nanoparticles. The stoichiometry of the metal precursors relative to the reducing agents in the plant extract influences the reduction efficiency and the resulting nanoparticle characteristics.

Reducing and Stabilizing Agents

The bioactive compounds present in the plant extract act as reducing and stabilizing agents. The types and concentrations of these compounds affect the reduction kinetics, particle growth, and stability. Understanding the specific roles of different bioactive compounds in nanoparticle synthesis is crucial for controlling the synthesis process [4].

External Factors

External factors, including light exposure, agitation, and the presence of additional additives or catalysts, can impact nanoparticle.

Characterization Techniques for Botanical Nanoparticles

Characterizing the physicochemical properties of nanoparticles synthesized using botanical materials is essential for understanding their structure, size, shape, composition, and stability. This section discusses the various characterization techniques employed for the analysis of botanical nanoparticles, including physical and chemical characterization methods and analytical techniques for size, shape, and composition analysis.

Physical and Chemical Characterization Methods

Transmission Electron Microscopy (TEM)

TEM is a powerful technique for visualizing nanoparticles at high resolution. It provides information about nanoparticle size, shape, and morphology. TEM allows for the direct observation of individual nanoparticles, enabling the determination of their size distribution and shape characteristics.

Scanning Electron Microscopy (SEM)

SEM is used to study the surface morphology and topography of nanoparticles. It provides information about the particle size, shape, and aggregation patterns. SEM analysis is particularly useful for examining the surface features and interactions between nanoparticles.

X-ray Diffraction (XRD)

XRD is employed to analyse the crystalline structure of nanoparticles. It reveals the arrangement of atoms within the nanoparticles and provides information about their crystallographic phases and crystal size. XRD patterns are used to identify the composition and crystallinity of the nanoparticles.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is a technique that measures the vibrational modes of molecular bonds in

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nanoparticles. It helps identify the functional groups present in the nanoparticles and provides information about the biomolecules or phytochemicals involved in nanoparticle synthesis. FTIR analysis can be used to confirm the presence of specific biomolecules as reducing and stabilizing agents.

UV-Visible Spectroscopy

UV-Visible spectroscopy is commonly used to determine the optical properties of nanoparticles, such as absorbance and surface plasmon resonance (SPR). It provides information about the nanoparticle size, shape, and concentration. The absorption spectra obtained from UV-Visible spectroscopy can be used to estimate the average particle size and assess the stability of the nanoparticles [5].

Analytical Techniques for Size, Shape, and Composition Analysis

Dynamic Light Scattering (DLS)

DLS measures the Brownian motion of nanoparticles in a liquid medium and provides information about their hydrodynamic size distribution. It is particularly useful for determining the size distribution and stability of nanoparticles in solution.

Atomic Force Microscopy (AFM)

AFM allows for the three-dimensional imaging and characterization of nanoparticles. It measures the interaction forces between the AFM probe and the nanoparticles, providing information about their size, shape, and surface roughness. AFM can be used for analyzing nanoparticles on solid substrates.

Energy-Dispersive X-ray Spectroscopy (EDS)

EDS is an analytical technique used in conjunction with SEM or TEM to determine the elemental composition of nanoparticles. It provides information about the presence and distribution of elements within the nanoparticles, helping to identify the composition and purity of the synthesized nanoparticles.

Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

ICP-MS is a sensitive technique used for quantitative analysis of the elemental composition of nanoparticles. It can determine the concentration of metals present in the nanoparticles, aiding in assessing the stoichiometry and purity of the synthesized nanoparticles.

X-ray Photoelectron Spectroscopy (XPS)

XPS provides information about the surface chemistry and elemental composition of nanoparticles. It analyzes the energies of emitted photoelectrons upon X-ray irradiation, allowing for the identification and quantification of elements present on the nanoparticle surface. XPS is useful for understanding the chemical state of the nanoparticles and the presence of surface functional groups [6].

Water Treatment Applications of Botanical Nanoparticles

Botanical nanoparticles have shown significant potential for various water treatment applications. Their unique properties and surface reactivity make them effective in the removal of contaminants from water sources. This section highlights the applications of botanical nanoparticles in the removal of contaminants and explores the mechanisms involved in adsorption, degradation, and disinfection processes.

Nanoparticles for Removal of Contaminants

Botanical nanoparticles have demonstrated efficacy in removing various contaminants from water sources, including heavy metals, organic pollutants, and pathogens. The adsorption capacity, surface reactivity, and high specific surface area of nanoparticles contribute to their effectiveness in contaminant removal.

Heavy Metal Removal

Botanical nanoparticles can effectively adsorb heavy metal ions, such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), from water. The functional groups on the surface of nanoparticles, derived from plant-based materials, facilitate the binding and immobilization of metal ions. This mechanism helps in reducing the concentration of heavy metals in water, thus improving its quality.

Organic Pollutant Removal

Botanical nanoparticles have shown promise in the removal of organic pollutants, including dyes, pesticides, pharmaceuticals, and industrial chemicals, from water. The adsorption capacity of nanoparticles, combined with their catalytic activity, facilitates the degradation and removal of organic pollutants through surface reactions. This process can lead to the detoxification of water sources and the elimination of harmful organic contaminants.

Pathogen Disinfection

Botanical nanoparticles exhibit antimicrobial properties that can aid in disinfecting water contaminated with pathogens such as bacteria, viruses, and fungi. The nanoparticles can directly interact with the pathogens, disrupting their cell membranes or inhibiting their metabolic processes. This antimicrobial activity helps in reducing the microbial load in water and preventing waterborne diseases.

Adsorption, Degradation, and Disinfection Mechanisms

The effectiveness of botanical nanoparticles in water treatment can be attributed to various mechanisms involved in adsorption, degradation, and disinfection processes:

Adsorption

The high surface area and functional groups present on the surface of nanoparticles enable effective adsorption of contaminants. The functional groups, derived from the plant-based materials, interact with the contaminants through electrostatic interactions, hydrogen bonding, or complexation. This adsorption mechanism helps in the immobilization and removal of contaminants from water.

Degradation

Nanoparticles can exhibit catalytic activity, facilitating the degradation of organic pollutants. The surface reactivity of nanoparticles enables them to catalyse oxidation or reduction reactions, leading to the breakdown of organic pollutants into less harmful compounds. The catalytic activity can be enhanced by incorporating specific plant-derived biomolecules or phytochemicals on the nanoparticle surface.

Disinfection

Botanical nanoparticles with antimicrobial properties can directly interact with pathogens, disrupting their cellular structures or inhibiting their growth and replication. The nanoparticles can penetrate the cell membranes of microorganisms, causing damage to their internal structures or interfering with their enzymatic processes. This antimicrobial mechanism aids in the disinfection of water and the prevention of waterborne diseases. In water treatment applications, the effectiveness of botanical nanoparticles is influenced by factors such as nanoparticle concentration, contact time, pH, temperature, and the nature of contaminants. Optimizing these parameters is crucial to achieve efficient removal, degradation, and disinfection processes [7].

Agricultural Applications of Botanical Nanoparticles

Botanical nanoparticles have gained significant attention in agricultural applications due to their potential for enhancing plant growth, disease management, nutrient uptake, and stress tolerance. This section explores the use of botanical nanoparticles in promoting plant growth and managing diseases, as well as their role in enhancing nutrient uptake and stress tolerance in plants.

Nanoparticles for Plant Growth Promotion and Disease Management

Botanical nanoparticles have been found to promote plant growth and provide protection against various plant diseases. The unique properties and bioactive compounds present in these nanoparticles contribute to their efficacy in agricultural applications.

Plant Growth Promotion

Botanical nanoparticles can stimulate plant growth by enhancing seed germination, root development, and overall plant biomass. The nanoparticles' small size and large surface area allow for better nutrient absorption, improved water retention, and increased root-soil interaction. Additionally, the phytochemicals present in the nanoparticles can act as growth regulators, promoting hormone synthesis and physiological processes in plants.

Disease Management

Botanical nanoparticles possess antimicrobial properties that can be beneficial for disease management in plants. These nanoparticles can directly interact with pathogens, inhibiting their growth, and preventing the spread of diseases. The nanoparticles' antimicrobial activity can help control fungal, bacterial, and viral infections in plants, reducing the need for chemical pesticides.

Enhancement of Nutrient Uptake and Stress Tolerance in Plants

Botanical nanoparticles have shown promise in enhancing nutrient uptake and improving stress tolerance in plants, thereby increasing their resilience to adverse environmental conditions.

Nutrient Uptake Enhancement

Botanical nanoparticles can improve the availability and uptake of essential nutrients by plants. The nanoparticles' high surface area and functional groups facilitate the chelation and solubilisation of nutrients, making them more accessible to plant roots. The nanoparticles can also enhance nutrient transport within plants, improving nutrient distribution to different plant tissues and organs.

Stress Tolerance

Botanical nanoparticles can help plants cope with various environmental stresses, such as drought, salinity, heavy metal toxicity, and temperature extremes. The nanoparticles can act as antioxidants, scavenging reactive oxygen species and reducing oxidative stress in plants. They can also regulate stress-related gene expression and signaling pathways, enhancing plant adaptation and survival under adverse conditions.The application of botanical nanoparticles in agriculture offers several advantages, including reduced reliance on chemical fertilizers

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and pesticides, improved resource-use efficiency, and sustainable crop production. However, further research is needed to understand the long-term effects, potential risks, and optimal application methods of these nanoparticles in agricultural systems [8].

Challenges and Future Prospects

The utilization of botanical biosynthesis for nanoparticle synthesis presents several challenges and limitations that need to be addressed. However, ongoing research and emerging trends offer promising strategies for improving nanoparticle synthesis and performance. This section discusses the challenges, potential drawbacks, strategies for improvement, and future directions in the field of botanical biosynthesis of nanoparticles.

Limitations and Potential Drawbacks of Botanical Biosynthesis

Variability in Nanoparticle Properties: Botanical biosynthesis can result in nanoparticles with variable properties, including size, shape, and composition. This variability arises from the complex nature of plant extracts and the influence of environmental factors on phytochemical composition. Ensuring consistent and reproducible nanoparticle synthesis remains a challenge.

Scale-up and Production Costs

Scaling up the synthesis of nanoparticles using botanical materials can be challenging and may require optimization of extraction methods, standardization of plant sources, and control of process parameters. Additionally, the cost-effectiveness of large-scale production needs to be considered, as it can influence the commercial viability of botanical nanoparticles.

Stability and Shelf Life

The stability and shelf life of botanical nanoparticles can be a concern due to potential degradation or aggregation over time. The presence of bioactive compounds in plant extracts may lead to changes in nanoparticle properties under different storage conditions. Developing strategies to enhance the stability and extend the shelf life of botanical nanoparticles is crucial for their practical applications [9].

Strategies for Improving Nanoparticle Synthesis and Performance

Standardization of Plant Sources and Extraction Methods

Standardizing the plant sources and extraction methods can help ensure consistency in nanoparticle synthesis. Identifying plants with high phytochemical content and well-defined extract composition can lead to more predictable nanoparticle properties [10].

Optimization of Synthesis Conditions

Fine-tuning the synthesis conditions, such as temperature, pH, reaction time, and concentrations of plant extract and metal precursors, can improve the control over nanoparticle synthesis. Understanding the influence of these parameters on nanoparticle properties and optimizing their values is essential for achieving desired performance.

Surface Functionalization and Modification

Surface functionalization of nanoparticles with specific biomolecules or polymers can enhance their stability, biocompatibility, and targeted functionality. Incorporating functional groups or ligands on the nanoparticle surface can improve their performance in various applications, such as catalysis, water treatment, and agricultural systems.

Emerging Trends and Future Directions

Hybrid Nanoparticles: Combining botanical nanoparticles with other nanomaterials, such as metal oxides, carbon-based nanomaterials, or quantum dots, can lead to the development of hybrid nanoparticles with enhanced properties. These hybrid systems can exhibit synergistic effects and offer improved performance in catalytic, water treatment, and agricultural applications[11].

Advanced Characterization Techniques

Advancements in characterization techniques, such as in situ monitoring, advanced microscopy, and spectroscopy methods, enable real-time observation and analysis of nanoparticle synthesis processes. These techniques provide valuable insights into the kinetics, mechanisms, and interactions involved in botanical nanoparticle synthesis [12].

Environmental Impact and Safety Assessment

As the field of botanical nanoparticle synthesis advances, it is important to conduct comprehensive assessments of their environmental impact and safety. Understanding the fate, behavior, and potential risks associated with the release of these nanoparticles into the environment is crucial for their responsible use.

Application-Specific Design

Tailoring the synthesis of botanical nanoparticles for specific applications can lead to optimized performance. Designing nanoparticles with desired properties, functionalities, and targeted delivery systems can enhance their efficacy in catalysis, water treatment, and agricultural applications [13,14].

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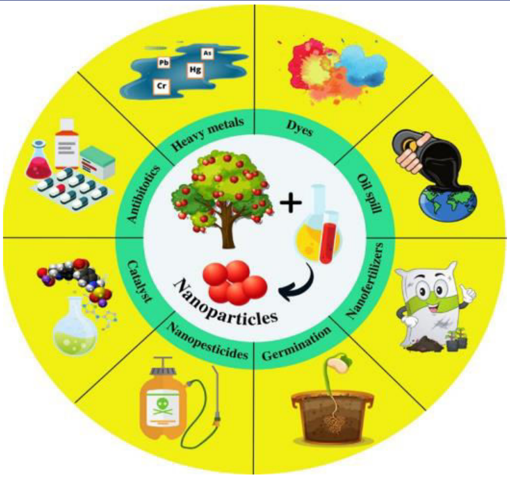

Fig.1 Biosynthesis of nanoparticles applications

Conclusion

Botanical biosynthesis of nanoparticles has emerged as a promising approach for the synthesis of nanomaterial with diverse applications. This review has provided an overview of recent developments in the field, highlighting the key findings and contributions related to catalytic, water treatment, and agricultural applications of botanical nanoparticles. Botanical biosynthesis offers several advantages, including eco-friendliness, cost-effectiveness, and the utilization of renewable resources. The use of plant extracts and phytochemicals in nanoparticle synthesis provides a sustainable alternative to conventional methods. The unique properties and bioactive compounds present in botanical nanoparticles contribute to their efficacy in catalysis, water treatment, and agricultural systems [15].

In catalytic applications, botanical nanoparticles have shown significant potential as catalysts for various reactions, offering high activity, selectivity, and stability. The use of plant-derived materials in catalysis aligns with the principles of green chemistry and sustainable development. In water treatment applications, botanical nanoparticles have demonstrated their effectiveness in the removal of contaminants, including heavy metals, organic pollutants, and pathogens. The adsorption, degradation, and disinfection mechanisms exhibited by these nanoparticles contribute to improved water quality and the prevention of waterborne diseases.

In agriculture, botanical nanoparticles have shown promise in promoting plant growth, managing diseases, enhancing nutrient uptake, and improving stress tolerance in plants. These nanoparticles offer sustainable solutions for improving crop productivity, reducing the use of chemical fertilizers and pesticides, and mitigating the impact of environmental stresses on plants. The importance of botanical biosynthesis in sustainable nanotechnology applications cannot be overstated. It offers a greener and more environmentally friendly approach to nanoparticle

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synthesis, minimizing the use of hazardous chemicals and reducing the environmental footprint. The utilization of plant-based materials aligns with the principles of sustainability, resource conservation, and circular economy.

While challenges and limitations exist, ongoing research and advancements in the field provide opportunities for improving nanoparticle synthesis methods, enhancing nanoparticle performance, and exploring novel applications. Standardization, optimization of synthesis conditions, surface functionalization, and advanced characterization techniques are key areas of focus for future research. In summary, botanical biosynthesis of nanoparticles holds great promise for catalytic, water treatment, and agricultural applications. It combines the benefits of nanotechnology with the sustainability and eco-friendliness of botanical materials, paving the way for the development of innovative and environmentally conscious solutions in various fields.

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