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Algae and Fungal Assisted Nanoparticle Synthesis and Their Applications in Energy Storage and Photocatalysis

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Abstract

The growing demand for sustainable nanomaterials has driven significant interest in biologically mediated synthesis routes, particularly those employing algae and fungi. These organisms provide an eco-friendly, cost-effective, and scalable alternative to conventional physicochemical methods for nanoparticle production. Algae and fungi possess diverse biomolecules—including proteins, polysaccharides, enzymes, and secondary metabolites—that act as reducing, stabilizing, and capping agents, enabling controlled nanoparticle synthesis. This review critically examines recent advances in algae- and fungal-assisted nanoparticle synthesis, focusing on synthesis mechanisms, physicochemical characteristics, and process optimization. Furthermore, it highlights the functional applications of these biogenic nanoparticles in energy storage systems such as supercapacitors, batteries, and hydrogen production, as well as in photocatalytic degradation of environmental pollutants. The role of nanoparticle morphology, surface chemistry, and bandgap engineering in enhancing photocatalytic and electrochemical performance is discussed in detail. Despite their advantages, challenges related to scalability, reproducibility, and long-term stability remain. Future research directions emphasize the integration of bio-assisted nanomaterials into hybrid systems, development of green synthesis protocols for industrial-scale production, and exploration of novel algal and fungal species. This review provides a comprehensive understanding of the potential of algae and fungi as biofactories for advanced nanomaterials, paving the way for sustainable energy and environmental technologies.

Keywords: *Biogenic nanoparticles, algae, fungi, green synthesis, photocatalysis, energy storage, nanobiotechnology.*

1. Introduction

Nanotechnology has emerged as a transformative field with far-reaching applications in energy, environmental remediation, medicine, and advanced materials. Nanoparticles, owing to their unique physicochemical properties such as high surface area-to-volume ratio, tunable morphology, and enhanced reactivity, have become integral to the development of next-generation technologies [1]. However, conventional methods for nanoparticle synthesis—primarily based on physical and chemical approaches—often involve toxic reagents, high energy consumption, and environmentally hazardous by-products. These limitations have prompted the scientific community to explore sustainable and eco-friendly alternatives.

In this context, biological systems such as algae and fungi have gained considerable attention as efficient and green nanofactories. These organisms possess inherent biochemical machinery capable of reducing metal ions into nanoparticles through enzymatic and non-enzymatic pathways. Algae, including microalgae and macroalgae, are rich in bioactive compounds such as polysaccharides, proteins, pigments, and phenolics, which act as natural reducing and stabilizing agents. Similarly, fungi exhibit high metal tolerance and secrete a variety of extracellular enzymes and metabolites that facilitate efficient nanoparticle synthesis [2]. The ability of these organisms to operate under ambient conditions further enhances their appeal for sustainable nanomaterial production.Biogenic synthesis not only reduces environmental impact but also offers improved control over nanoparticle characteristics. Parameters such as particle size, shape, crystallinity, and surface functionality can be modulated through biological and environmental conditions, enabling the design of application-specific nanomaterials. Moreover, the presence of natural capping agents derived from biological systems enhances nanoparticle stability and biocompatibility, which is particularly advantageous for environmental and energy-related applications.

Recent studies have demonstrated that nanoparticles synthesized using algae and fungi exhibit enhanced properties, including improved surface area, controlled morphology, and superior catalytic efficiency. These features make them highly suitable for applications in energy storage systems and photocatalytic processes.

For instance, biogenic metal oxide nanoparticles have shown promising performance in supercapacitors, batteries, and hydrogen production systems, while also demonstrating high efficiency in the photocatalytic degradation of organic pollutants and wastewater treatment.

The integration of such biologically synthesized nanomaterials into sustainable technological frameworks represents a critical step toward addressing global challenges related to energy demand, environmental pollution, and resource depletion [3]. Despite significant progress, challenges such as scalability, reproducibility, and mechanistic understanding remain to be fully resolved. Therefore, a comprehensive evaluation of synthesis strategies, material properties, and application potential is essential.This review aims to provide an in-depth analysis of algae and fungal-assisted nanoparticle synthesis, focusing on underlying mechanisms, characterization, and their emerging applications in energy storage and photocatalysis. It also highlights current challenges and future perspectives to guide further research and technological advancement in this rapidly evolving field.

2. Mechanisms of Algae and Fungal Mediated Nanoparticle Synthesis

The biosynthesis of nanoparticles using algae and fungi involves intricate biochemical and physicochemical interactions that enable the reduction of metal ions into stable nanoscale structures. These processes are broadly categorized into intracellular and extracellular synthesis pathways, both governed by the metabolic activity and biochemical composition of the organisms.In algal-mediated synthesis, the process is primarily driven by photosynthetic electron transport chains and metabolite secretion. Algae produce a wide spectrum of biomolecules, including polysaccharides, proteins, lipids, pigments, and phenolic compounds, which function as reducing and capping agents [4]. The reduction of metal ions such as Ag^{+}, Au^{3+}, and Zn^{2+} occurs through electron donation from these biomolecules, leading to nucleation and subsequent growth of nanoparticles. Extracellular synthesis is particularly advantageous in algae, as secreted metabolites facilitate nanoparticle formation outside the cell, simplifying downstream purification. Additionally, the presence of sulfated polysaccharides and pigments such as chlorophyll enhances metal binding and stabilization, contributing to controlled particle morphology.

Fungal-mediated synthesis, on the other hand, is highly efficient due to the organism's extensive mycelial network and high secretion capacity of enzymes. Enzymes such as nitrate reductase, along with cofactors like NADH and NADPH, play a pivotal role in reducing metal ions [5]. Fungi can accumulate large amounts of biomass, enabling higher nanoparticle yields compared to many other biological systems. Intracellular synthesis involves the transport of metal ions into the cell, where enzymatic reduction occurs, whereas extracellular synthesis relies on secreted enzymes and metabolites. The latter is more industrially viable due to ease of nanoparticle recovery. Moreover, fungal proteins act as natural stabilizing agents, preventing aggregation and enhancing nanoparticle stability.Several environmental and operational parameters critically influence the synthesis process. Factors such as pH, temperature, precursor concentration, reaction time, and biomass density determine the size, shape, crystallinity, and yield of nanoparticles. For instance, alkaline pH conditions generally favor smaller particle sizes due to increased reduction rates, while higher temperatures can accelerate nucleation but may also lead to aggregation.

Understanding and optimizing these parameters is essential for achieving reproducibility and scalability in biogenic nanoparticle synthesis.

3. Types and Characterization of Biogenic Nanoparticles

Algae and fungi are capable of synthesizing a diverse range of nanoparticles with distinct physicochemical properties, making them suitable for various technological applications. These include metallic nanoparticles such as silver (Ag), gold (Au), and copper (Cu), as well as metal oxide nanoparticles like zinc oxide (ZnO), titanium dioxide (TiO_2), and iron oxide (Fe_3O_4). Additionally, recent advancements have enabled the synthesis of doped and composite nanomaterials, which exhibit enhanced functional properties due to synergistic interactions between multiple components.The type of nanoparticle produced is largely dependent on the precursor material and the biological system used. For example, algal extracts rich in polysaccharides tend to produce well-dispersed metal nanoparticles, while fungal systems are particularly effective in generating metal oxide nanoparticles with high crystallinity [6]. The ability to tailor nanoparticle characteristics through biological routes offers a significant advantage over conventional synthesis methods.Comprehensive characterization of these nanoparticles is essential to understand their structural, optical, and functional properties. UV–Visible spectroscopy is commonly employed to monitor nanoparticle formation through surface plasmon resonance peaks, which provide insights into particle size and distribution. X-ray diffraction (XRD) analysis is used to determine crystalline structure and phase purity, confirming the formation of specific nanomaterials. Electron microscopy techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide detailed information on morphology, size, and dispersion.Fourier-transform infrared spectroscopy (FTIR) plays a crucial role in identifying functional groups involved in reduction and stabilization, thereby elucidating the interaction between biomolecules and nanoparticles [7]. Dynamic light scattering (DLS) and zeta potential measurements further contribute to understanding particle size distribution and colloidal stability. Together, these characterization techniques provide a comprehensive framework for evaluating the quality and applicability of biogenic nanoparticles in advanced technological applications.

4. Applications in Energy Storage

The application of biogenically synthesized nanoparticles in energy storage systems has gained significant attention due to their unique structural and electrochemical properties. The high surface area-to-volume ratio, tunable morphology, and enhanced conductivity of these nanoparticles make them ideal candidates for improving the performance of energy storage devices such as supercapacitors, batteries, and hydrogen production systems.In supercapacitors, biogenic nanoparticles contribute to improved charge storage capacity and rapid charge–discharge cycles. Metal oxide nanoparticles such as MnO_2, ZnO, and Fe_3O_4 synthesized using algae and fungi exhibit excellent pseudocapacitive behavior, which enhances energy density and cycling stability [8]. The presence of bio-organic capping agents can also improve electrode–electrolyte interactions, leading to better electrochemical performance.

In battery technologies, particularly lithium-ion and sodium-ion batteries, biogenic nanoparticles are used as electrode materials to enhance energy density, conductivity, and structural integrity. For instance, iron oxide and titanium dioxide nanoparticles synthesized through fungal routes have demonstrated improved lithium storage capacity and reduced volume expansion during charge–discharge cycles. The incorporation of these nanoparticles into composite electrodes further enhances their performance by providing better electron transport pathways and mechanical stability.Hydrogen production through photocatalytic water splitting represents another promising application. Biogenic nanoparticles, especially semiconductor metal oxides, act as efficient photocatalysts by absorbing light and generating electron–hole pairs that drive the water-splitting reaction. The eco-friendly synthesis of such catalysts using algae and fungi aligns well with the principles of sustainable energy production. Furthermore, surface modification and doping strategies can be employed to enhance light absorption and catalytic efficiency, making these materials highly suitable for next-generation renewable energy systems.

Table 1: Algae and Fungal Assisted Nanoparticle Synthesis and Their Applications

Biological Source	Type of Nanoparticle	Biomolecules Involved	Synthesis Mode	Applications in Energy Storage	Applications in Photocatalysis
Microalgae (e.g., *Chlorella*, *Spirulina*)	Ag, Au, ZnO	Proteins, polysaccharides, pigments	Extracellular	Supercapacitors, electrode materials	Dye degradation, wastewater treatment
Macroalgae (e.g., *Sargassum*, *Ulva*)	Fe_3O_4, TiO_2	Sulfated polysaccharides, phenolics	Extracellular	Battery components, conductive materials	Organic pollutant degradation
Filamentous fungi (e.g., *Aspergillus*, *Fusarium*)	Ag, Au, Fe_3O_4	Enzymes (nitrate reductase), proteins	Intra- & extracellular	Lithium-ion batteries, energy storage devices	Photocatalytic oxidation, water purification
Yeasts (e.g., *Saccharomyces cerevisiae*)	CdS, ZnS	Amino acids, peptides	Intracellular	Semiconductor materials for energy systems	Light-driven catalytic reactions
Marine algae	CuO, TiO_2	Pigments, proteins, lipids	Extracellular	Hydrogen production catalysts	CO_2 reduction, advanced photocatalysis
Endophytic fungi	Metal oxides, hybrid nanoparticles	Secondary metabolites	Extracellular	Nanocomposite electrodes	Degradation of emerging contaminants

5. Applications in Photocatalysis

Photocatalysis is one of the most significant application areas of biogenic nanoparticles, particularly in environmental remediation and sustainable energy conversion. The ability of these nanoparticles to harness light energy and generate reactive species makes them highly effective in degrading pollutants and facilitating chemical transformations [9]. One of the primary applications is the degradation of organic pollutants, including dyes, pharmaceuticals, and pesticides, commonly found in industrial wastewater. Biogenic nanoparticles such as ZnO and TiO_2 generate reactive oxygen species (ROS), including hydroxyl radicals and superoxide ions, upon light irradiation. These reactive species oxidize complex organic molecules into simpler, non-toxic compounds such as carbon dioxide and water. The presence of bio-derived capping agents enhances the dispersion and stability of nanoparticles, thereby improving their photocatalytic efficiency.In water purification systems, these nanoparticles are employed not only for pollutant degradation but also for microbial disinfection. The combined effects of photocatalysis and antimicrobial activity enable the removal of both chemical and biological contaminants, making the process highly effective for wastewater treatment. Additionally, the reusability and stability of biogenic nanoparticles further enhance their practical applicability in large-scale systems.Emerging applications of photocatalysis include the reduction of carbon dioxide into value-added fuels such as methane and methanol. This process, known as photocatalytic CO_2 reduction, holds immense potential for addressing climate change by converting greenhouse gases into useful energy resources. Biogenic nanoparticles, with their tunable bandgap and surface properties, can be engineered to optimize light absorption and catalytic activity for such applications.Despite these advancements, challenges such as recombination of electron–hole pairs, limited light absorption range, and catalyst deactivation need to be addressed. Ongoing research focuses on developing hybrid nanostructures, doping strategies, and surface modifications to overcome these limitations and enhance overall photocatalytic performance.

6. Advantages of Algae and Fungal Assisted Nanoparticle Synthesis

The use of algae and fungi for nanoparticle synthesis offers several distinct advantages over conventional physicochemical methods, positioning them as promising alternatives in green nanotechnology. One of the most significant benefits is their eco-friendly nature, as these biological systems eliminate the need for toxic reducing agents, high-energy inputs, and hazardous solvents. The synthesis process typically occurs under mild conditions of temperature and pressure, thereby reducing energy consumption and environmental impact.Another key advantage lies in cost-effectiveness and scalability. Algae and fungi can be cultivated using relatively inexpensive substrates, including wastewater and agricultural residues, making the process economically viable for large-scale production. Their rapid growth rates and high biomass yield further enhance productivity. Additionally, the ability of these organisms to secrete large quantities of biomolecules facilitates extracellular nanoparticle synthesis, simplifying downstream processing and purification [10]. Biogenic nanoparticles are also inherently biocompatible and less toxic due to the presence of natural capping agents such as proteins, polysaccharides, and lipids. These biomolecules not only stabilize the nanoparticles but also impart functional properties that enhance their performance in applications such as catalysis, energy storage, and environmental remediation. Furthermore, the biological synthesis route allows for better control over nanoparticle size, shape, and surface characteristics through manipulation of growth conditions, the versatility of algae and fungi enables the synthesis of a wide range of nanomaterials, including metals, metal oxides, and hybrid nanostructures [11]. This adaptability, combined with sustainability and functional efficiency, makes biological synthesis a highly attractive approach for next-generation nanomaterial production.

7. Challenges and Limitations

The numerous advantages associated with algae and fungal-mediated nanoparticle synthesis, several challenges hinder their widespread adoption and industrial-scale application. One of the primary limitations is the lack of reproducibility and consistency in nanoparticle synthesis.

Biological systems are inherently variable, and slight changes in environmental conditions, growth phases, or metabolic activity can lead to significant variations in nanoparticle size, morphology, and yield.Another major challenge is the limited control over nanoparticle uniformity and monodispersity. Unlike chemical synthesis methods, which offer precise control over reaction parameters, biological processes often result in heterogeneous nanoparticle populations. This variability can affect the performance of nanoparticles in applications such as catalysis and energy storage, where uniformity is critical.Scalability remains a significant concern. While laboratory-scale synthesis has been extensively demonstrated, translating these processes to industrial-scale production poses technical and economic challenges. Issues such as maintaining sterile conditions, optimizing biomass production, and ensuring efficient recovery of nanoparticles need to be addressed. Additionally, the downstream processing of nanoparticles, including separation, purification, and drying, can be complex and resource-intensive.Stability and storage of biogenic nanoparticles also present challenges. The presence of organic capping agents, while beneficial for stabilization, may lead to degradation over time, affecting the long-term performance of the nanoparticles. Furthermore, incomplete understanding of the underlying biochemical mechanisms limits the ability to optimize and standardize the synthesis process, these challenges requires interdisciplinary research efforts aimed at improving process control, developing robust scale-up strategies, and enhancing the stability and functionality of biogenic nanoparticles.

8. Future Perspectives

The future of algae and fungal-assisted nanoparticle synthesis lies in the integration of advanced biotechnological and nanotechnological approaches to overcome existing limitations and unlock new application domains. One promising direction is the use of genetic and metabolic engineering to enhance the nanoparticle-producing क्षमता of algae and fungi. By modifying specific metabolic pathways, it is possible to increase the production of reducing agents and tailor the synthesis process for desired nanoparticle characteristics.The development of hybrid nanomaterials represents another important avenue for future research. Combining biogenic nanoparticles with other functional materials, such as carbon-based nanostructures or conductive polymers, can significantly enhance their performance in energy storage and photocatalytic applications. Such hybrid systems can address issues related to charge transfer, stability, and catalytic efficiency.Artificial intelligence (AI) and machine learning (ML) tools are also expected to play a crucial role in optimizing synthesis parameters and predicting nanoparticle properties. By analyzing large datasets, these technologies can help identify optimal conditions for achieving desired nanoparticle characteristics, thereby improving reproducibility and scalability, the exploration of novel algal and fungal species with unique metabolic capabilities can expand the diversity of biogenic nanoparticles. Marine algae, extremophilic fungi, and genetically engineered strains offer untapped potential for producing nanoparticles with unique properties.From an application perspective, the integration of biogenic nanoparticles into real-world systems, such as wastewater treatment plants, solar energy devices, and energy storage systems, will be a key focus. Life-cycle assessment and environmental impact studies will also be essential to ensure the sustainability and safety of these technologies.

Overall, continued innovation and interdisciplinary collaboration will drive the transition of biogenic nanoparticle synthesis from laboratory research to industrial implementation.

9. Conclusion

Algae and fungal-assisted nanoparticle synthesis represents a paradigm shift in the field of nanotechnology, offering a sustainable, eco-friendly, and versatile alternative to conventional synthesis methods. The ability of these biological systems to produce a wide range of nanoparticles under mild conditions highlights their potential as efficient biofactories for advanced nanomaterials. The unique physicochemical properties of biogenic nanoparticles, including enhanced surface functionality, stability, and catalytic activity, make them highly suitable for applications in energy storage and photocatalysis.The integration of these nanoparticles into energy systems such as supercapacitors, batteries, and hydrogen production technologies demonstrates their capability to address critical challenges in energy sustainability. Similarly, their application in photocatalytic degradation of pollutants and water purification underscores their importance in environmental remediation. These advancements collectively contribute to the development of green and sustainable technologies, the transition from laboratory-scale research to industrial-scale application requires addressing key challenges related to reproducibility, scalability, and mechanistic understanding. Advances in biotechnology, materials science, and computational tools are expected to play a crucial role in overcoming these limitations. Future research should focus on developing standardized protocols, enhancing nanoparticle stability, and exploring novel biological systems, algae and fungi hold immense potential as sustainable sources for nanoparticle synthesis. Their integration into emerging technologies offers a promising pathway toward achieving environmental sustainability and energy efficiency.

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