

Green Synthesis of Nanomaterials for Water Purification: A Sustainable Approach for Developing Regions

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ABSTRACT

The Green synthesis of nanomaterials has emerged as an innovative and eco-friendly approach for water purification, particularly in developing regions facing acute water scarcity and pollution challenges. Unlike conventional chemical and physical synthesis methods, green synthesis utilizes biological agents such as plant extracts, microorganisms, and natural polymers, reducing the use of toxic chemicals and energy consumption. This sustainable technique enables the production of nanoparticles with enhanced properties, including high surface area, catalytic efficiency, and antimicrobial activity, making them highly effective in removing contaminants such as heavy metals, dyes, pathogens, and organic pollutants from water. In developing countries, where access to advanced water treatment technologies is limited, green-synthesized nanomaterials offer a cost-effective and locally adaptable solution. Materials such as silver nanoparticles, zinc oxide, and iron-based nanomaterials have shown promising results in improving water quality while minimizing environmental impact. Furthermore, the use of readily available natural resources enhances community participation and scalability. This study highlights the potential of green nanotechnology in addressing water purification challenges, emphasizing its role in promoting sustainable development, environmental protection, and public health. It concludes that integrating green synthesis methods into water treatment systems can significantly contribute to achieving safe and clean water access in resource-constrained settings.

Keywords: Green Synthesis, Purification Challenges, Treatment Systems, Clean Water

Introduction

Access to safe and clean drinking water is one of the most fundamental human needs and a critical component of sustainable development. Despite significant global progress in water supply infrastructure, billions of people—particularly in developing regions—still lack reliable access to potable water. According to the World Health Organization (WHO, 2023), nearly 2 billion people worldwide consume water contaminated with fecal matter, heavy metals, industrial effluents, and emerging organic pollutants. This crisis is especially severe in South Asia, Sub-Saharan Africa, and parts of Latin America, where rapid urbanization, industrial expansion, and weak

environmental regulations exacerbate water quality degradation (UNICEF, 2022). Conventional water purification technologies such as chlorination, coagulation, sedimentation, and membrane filtration have been widely adopted; however, they present significant limitations. These methods are often expensive, energy-intensive, and ineffective in completely removing micro-pollutants such as pharmaceuticals, dyes, and heavy metals at trace concentrations (Shannon et al., 2008). Moreover, many of these processes generate secondary pollutants or toxic sludge, which require additional treatment and disposal. As a result, there is a growing demand for innovative, sustainable, and cost-effective water treatment technologies that can be applied in resource-limited settings.

In this context, nanotechnology has emerged as a transformative field with immense potential in environmental remediation, particularly water purification. Nanomaterials, defined as materials with at least one dimension between 1 and 100 nanometers, exhibit unique physicochemical properties such as high surface area-to-volume ratio, enhanced reactivity, and tunable optical and catalytic behavior (Khan et al., 2019). These properties make them highly effective in adsorbing contaminants, catalyzing pollutant degradation, and eliminating microbial pathogens from water systems. Various nanomaterials, including silver nanoparticles (AgNPs), titanium dioxide (TiO₂), zinc oxide (ZnO), and iron oxide (Fe₃O₄), have demonstrated strong potential in water treatment applications. However, conventional methods for synthesizing nanomaterials often involve toxic reducing agents, high energy consumption, and hazardous by-products, raising serious environmental and health concerns. Chemical and physical synthesis routes typically rely on substances such as sodium borohydride, hydrazine, or organic solvents, which are not environmentally sustainable (Iravani, 2011). These limitations have led researchers to explore greener and more sustainable approaches for nanomaterial synthesis.

The Green synthesis of nanomaterials has emerged as an eco-friendly alternative that aligns with the principles of green chemistry. This approach utilizes biological resources such as plant extracts, bacteria, fungi, algae, and agricultural waste as reducing and stabilizing agents in nanoparticle formation (Ahmed et al., 2016). Phytochemicals present in plant extracts, including flavonoids, alkaloids, phenolics, and terpenoids, play a crucial role in reducing metal ions into stable nanoparticles while simultaneously preventing aggregation. This biological route eliminates the need for toxic chemicals, reduces energy consumption, and enhances the environmental compatibility of nanoparticle production. The Plant-mediated synthesis is the most widely studied green synthesis method due to its simplicity, cost-effectiveness, and scalability. For instance, extracts from neem (*Azadirachta indica*), green tea (*Camellia sinensis*), and aloe vera (*Aloe barbadensis*) have been successfully used to synthesize metal nanoparticles with excellent antimicrobial and catalytic properties (Mittal et al., 2013). Similarly, microbial synthesis involving bacteria and fungi offers precise control over nanoparticle morphology and size distribution, making it suitable for specialized applications in water purification systems (Singh et al., 2018).

The application of green-synthesized nanomaterials in water purification is based on multiple mechanisms, including adsorption, photo catalysis, and antimicrobial activity. Nanoparticles can effectively adsorb heavy metals such as lead (Pb²⁺),

arsenic (As^{3+}), and mercury (Hg^{2+}) due to their high surface reactivity and functionalized surfaces. In photocatalytic processes, semiconductor nanomaterials such as TiO_2 generate reactive oxygen species (ROS) under light exposure, which degrade organic pollutants like dyes, pesticides, and pharmaceutical residues into less harmful compounds (Chong et al., 2010). Additionally, silver and zinc oxide nanoparticles exhibit strong antimicrobial properties by disrupting bacterial cell membranes and interfering with cellular metabolic processes, making them effective for disinfection purposes (Rai et al., 2009). Developing regions face unique challenges that make green nanotechnology particularly relevant. In rural and peri-urban areas, centralized water treatment infrastructure is often absent or insufficient. Households rely heavily on groundwater, surface water, or untreated municipal supplies, which are frequently contaminated. Green nanomaterials offer a decentralized, low-cost, and scalable solution that can be integrated into household filtration systems, community water treatment units, and portable purification devices. Moreover, the use of locally available biological resources for nanoparticle synthesis reduces dependency on imported chemicals and advanced industrial infrastructure.

Despite these advantages, several challenges hinder the large-scale implementation of green nanomaterials in water purification systems. One of the major concerns is the scalability of synthesis methods. While laboratory-scale production is well established, industrial-scale synthesis with consistent quality control remains a challenge. Additionally, the long-term environmental and human health impacts of nanomaterial exposure are not fully understood, raising concerns about nanoparticle toxicity, bioaccumulation, and ecological risks (Baker et al., 2014).

The Recovery and reuse of nanomaterials from treated water also remain technically challenging, limiting their practical deployment. Another critical issue is the lack of standardized regulatory frameworks governing the production, use, and disposal of nanomaterials in many developing countries. Without proper regulation, there is a risk of unmonitored environmental release of nanoparticles, which could potentially disrupt aquatic ecosystems. Therefore, interdisciplinary research integrating environmental science, chemistry, engineering, and policy studies is essential to ensure the safe and sustainable application of green nanotechnology. The recent advancements in hybrid systems combining green nanomaterials with conventional filtration technologies such as membrane filtration, activated carbon, and bio-sand filters have shown promising results. These integrated systems enhance purification efficiency while maintaining cost-effectiveness and environmental sustainability. Furthermore, innovations in nanocomposite materials and magnetic nanoparticles have improved recovery and reusability, addressing one of the key limitations of nanotechnology-based water treatment systems (Das et al., 2020).

The green synthesis of nanomaterials represents a revolutionary approach to addressing global water purification challenges, particularly in developing regions. By leveraging natural biological systems for nanoparticle production, this approach minimizes environmental impact while maximizing efficiency in contaminant removal. Although significant challenges remain in scalability, toxicity assessment, and regulatory governance, continued research and technological innovation hold great promise for the future. The integration of green nanotechnology into water treatment systems can play a pivotal role in achieving Sustainable Development Goal

6, which aims to ensure availability and sustainable management of water and sanitation for all.

Green Synthesis of Nanomaterials

Green synthesis of nanomaterials is an emerging and sustainable approach in nanotechnology that focuses on the environmentally friendly production of nanoparticles using biological resources such as plant extracts, microorganisms, and agricultural waste. Unlike conventional physical and chemical methods that rely on toxic reagents and high energy consumption, green synthesis utilizes naturally occurring biomolecules like flavonoids, alkaloids, phenolics, and enzymes as reducing and stabilizing agents for nanoparticle formation. This approach not only minimizes environmental pollution and health risks but also offers a cost-effective and scalable alternative for producing nanomaterials with controlled size and shape. In recent years, green-synthesized nanomaterials have gained significant attention for their applications in water purification, particularly in removing heavy metals, degrading organic pollutants, and eliminating pathogenic microorganisms. (Ponce, et al, 2023).

Concept of Green Synthesis

Green synthesis is an eco-friendly and sustainable approach for producing nanomaterials by utilizing natural biological systems instead of hazardous chemicals. In this method, plant extracts, microorganisms, and agro-waste act as both reducing and stabilizing agents in the formation of nanoparticles. Plant-mediated synthesis is the most widely used technique because different parts of plants such as leaves, roots, stems, flowers, and fruits contain bioactive compounds like flavonoids, alkaloids, tannins, and phenolic acids. These compounds help in reducing metal ions into stable nanoparticles while also controlling their growth and preventing aggregation. This makes the process simple, cost-effective, and environmentally safe, as it avoids the use of toxic chemicals and high-energy inputs commonly required in conventional synthesis methods. In addition to plants, bacteria and fungi also play an important role in green synthesis of nanomaterials. Microorganisms can absorb metal ions and convert them into nanoparticles through enzymatic and metabolic processes, allowing precise control over particle size and shape. Fungi are particularly useful due to their high tolerance to metals and ability to produce large quantities of nanoparticles extracellularly, making recovery easier. Similarly, agricultural waste such as fruit peels, husks, and plant residues can also be utilized as low-cost raw materials for nanoparticle synthesis, supporting waste valorization and circular economy principles. Together, these biological systems provide a sustainable pathway for producing nanomaterials that are highly applicable in environmental remediation, especially water purification in developing regions.

Common Green Synthesized Nanomaterials

Common green-synthesized nanomaterials include a variety of metal and metal-oxide nanoparticles that are widely used in environmental applications, especially water purification. Among them, silver nanoparticles (AgNPs) are the most extensively studied due to their strong antimicrobial properties. They are highly effective in eliminating bacteria, viruses, and other pathogens from contaminated water by

disrupting cell membranes and interfering with cellular functions. Zinc oxide nanoparticles (ZnO NPs) are also commonly used because of their photocatalytic and antibacterial activities. Under light exposure, ZnO nanoparticles generate reactive oxygen species (ROS), which help degrade organic pollutants and disinfect water. The Iron oxide nanoparticles (Fe_3O_4 NPs) are another important class of green-synthesized materials, particularly valued for their magnetic properties, which allow easy separation and recovery from treated water. These nanoparticles are highly effective in removing heavy metals and arsenic due to their strong adsorption capacity. Similarly, titanium dioxide nanoparticles (TiO_2 NPs) are widely used photo catalysts that degrade organic contaminants such as dyes, pesticides, and pharmaceutical residues when exposed to ultraviolet or sunlight. Together, these green-synthesized nanomaterials offer efficient, sustainable, and versatile solutions for addressing water pollution challenges, especially in developing regions with limited access to advanced treatment technologies (Ismail, et,al 2025).

Mechanism of Formation of Green-Synthesized Nanomaterials

The formation of nanomaterials through green synthesis occurs via a biologically driven reduction and stabilization process in which plant extracts, microorganisms, or agricultural wastes convert metal ions into stable nanoparticles. The process typically begins when metal salt precursors (such as Ag^+ , Zn^{2+} , Fe^{3+} , or Ti^{4+} ions) are introduced into a biological extract containing active biomolecules. These biomolecules—such as flavonoids, phenolics, proteins, enzymes, and sugars—act as natural reducing agents that donate electrons to metal ions, converting them into zero-valent atoms. Once reduced, these atoms undergo nucleation, where small clusters form and serve as seeds for further particle growth. Following nucleation, the nanoparticles grow through aggregation of reduced atoms until they reach a thermodynamically stable size. During this stage, biomolecules present in the biological medium also act as capping or stabilizing agents, binding to the nanoparticle surface and preventing uncontrolled agglomeration. This stabilization is crucial for controlling particle size, shape, and dispersion, which directly influence the physicochemical properties and efficiency of nanomaterials in water purification applications. In microbial synthesis, bacteria and fungi play a slightly different role, as they produce enzymes that facilitate the intracellular or extracellular reduction of metal ions. Fungi are particularly efficient due to their high secretion of proteins and large biomass, which enhances nanoparticle yield. Overall, the green synthesis mechanism is a coordinated process involving reduction, nucleation, growth, and stabilization, resulting in eco-friendly nanomaterials with controlled characteristics suitable for environmental remediation.

Applications of Green-Synthesized Nanomaterials in Water Purification

Green-synthesized nanomaterials have gained significant attention in water purification due to their high efficiency, eco-friendly nature, and multifunctional properties. One of their most important applications is the removal of heavy metals such as lead (Pb^{2+}), arsenic (As^{3+}), mercury (Hg^{2+}), and cadmium (Cd^{2+}) from contaminated water. Nanoparticles like iron oxide (Fe_3O_4) and zinc oxide (ZnO) exhibit strong adsorption capacities due to their large surface area and active binding sites, allowing them to effectively capture and immobilize toxic metal ions, making water safe for consumption.

Removal of Heavy Metals

Green-synthesized nanomaterials are highly effective in removing toxic heavy metals from contaminated water due to their large surface area, high reactivity, and presence of functional groups derived from biological synthesis. Metals such as lead (Pb^{2+}), arsenic (As^{3+}), and cadmium (Cd^{2+}) are particularly dangerous because they are non-biodegradable and can accumulate in living organisms, leading to severe health problems including kidney damage, neurological disorders, and cancer. Nanomaterials like iron oxide (Fe_3O_4), zinc oxide (ZnO), and plant-mediated silver nanoparticles (AgNPs) provide efficient adsorption sites that bind these metal ions through electrostatic attraction, ion exchange, and surface complexation mechanisms. Iron oxide nanoparticles are especially effective in arsenic removal due to their strong affinity for oxyanions, allowing arsenic to be adsorbed and separated from water easily using magnetic recovery techniques. Similarly, cadmium and lead ions are efficiently captured by green-synthesized nanoparticles through surface functional groups such as hydroxyl ($-\text{OH}$), carboxyl ($-\text{COOH}$), and amino ($-\text{NH}_2$) groups present on the nanoparticle surface. These interactions convert dissolved metal ions into stable complexes, significantly reducing their concentration in water. As a result, green nanomaterials offer a sustainable, low-cost, and highly efficient solution for heavy metal remediation, particularly suitable for developing regions facing industrial and groundwater contamination challenges.

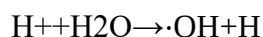
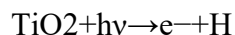
Organic Pollutant Degradation Using Green-Synthesized Nanoparticles

Organic pollutants in water—such as synthetic dyes, pesticides, and pharmaceutical residues—are persistent, toxic, and often resistant to conventional treatment methods. Green-synthesized semiconductor nanoparticles, particularly **titanium dioxide (TiO_2)** and **zinc oxide (ZnO)**, have emerged as highly efficient photo catalysts for degrading these contaminants into less harmful or mineralized products.

Photocatalytic Mechanism of TiO_2 and ZnO

Both TiO_2 and ZnO are wide-bandgap semiconductors. When exposed to ultraviolet (UV) or, in some modified forms, visible light, they become activated and generate reactive species.

Core mechanism:



Organic Pollutant Degradation

Green-synthesized nanomaterials play a vital role in the degradation of organic pollutants present in contaminated water, particularly those originating from industrial, agricultural, and pharmaceutical sources. These pollutants include synthetic dyes, pesticides, herbicides, antibiotics, and other persistent organic compounds that are resistant to natural degradation and can accumulate in aquatic ecosystems. Nanomaterials such as titanium dioxide (TiO_2), zinc oxide (ZnO), and silver-based composites are widely used for this purpose due to their strong photocatalytic and oxidative properties.

The degradation process primarily occurs through photo catalysis, where semiconductor nanoparticles absorb light energy (UV or sunlight) and generate

electron-hole pairs. These charge carriers react with water and oxygen molecules to produce highly reactive oxygen species (ROS) such as hydroxyl radicals ($\bullet\text{OH}$) and superoxide radicals ($\text{O}_2^{\bullet-}$). These reactive species are extremely powerful oxidizing agents that break down complex organic pollutants into simpler, non-toxic end products such as carbon dioxide, water, and inorganic ions. This process not only eliminates harmful contaminants but also prevents the formation of secondary pollutants.

Antimicrobial Activity

Green-synthesized nanomaterials exhibit strong antimicrobial activity, making them highly effective for water disinfection and pathogen control. Contaminated water in many developing regions often contains harmful microorganisms such as bacteria, viruses, fungi, and protozoa that cause waterborne diseases including cholera, typhoid, dysentery, and hepatitis. Nanomaterials such as silver nanoparticles (AgNPs), zinc oxide (ZnO), and iron-based composites are widely recognized for their ability to inactivate these pathogens efficiently and sustainably.

The antimicrobial mechanism of these nanoparticles is mainly based on multiple interacting pathways. First, nanoparticles attach to the microbial cell wall through electrostatic attraction, leading to structural damage and increased membrane permeability. This disrupts the integrity of the cell, causing leakage of essential intracellular components. Second, many nanomaterials generate reactive oxygen species (ROS), which induce oxidative stress inside microbial cells. These ROS damage proteins, lipids, and DNA, ultimately leading to cell death. Third, silver nanoparticles are known to penetrate microbial cells and interact with sulfur- and phosphorus-containing biomolecules, thereby interfering with enzyme function and genetic replication.

Green synthesis further enhances antimicrobial performance because plant-derived biomolecules acting as capping agents improve nanoparticle stability and dispersion, increasing their contact with microorganisms. Additionally, the eco-friendly nature of these nanoparticles reduces the risk of introducing harmful chemical residues into drinking water. As a result, green-synthesized nanomaterials provide an efficient, low-cost, and sustainable solution for water disinfection, particularly suitable for decentralized water treatment systems in developing regions where access to conventional purification infrastructure is limited.

Advantages of Green Nanotechnology

Green nanotechnology offers a wide range of environmental, economic, and social benefits, making it a highly promising approach for sustainable water purification and environmental remediation. One of its most important advantages is its environmental friendliness. Unlike conventional chemical and physical methods, green synthesis avoids the use of toxic reducing agents, hazardous solvents, and high-energy processes. Instead, it relies on natural biological resources such as plant extracts, microorganisms, and agricultural waste, significantly reducing environmental pollution and chemical waste generation.

Another major advantage is its cost-effectiveness. Green synthesis uses readily available and renewable biological materials, which reduces production costs and makes nanomaterials more accessible for developing regions. This is particularly important for rural and low-income communities where expensive water treatment

technologies are not feasible. Additionally, the process often occurs under mild conditions such as room temperature and atmospheric pressure, further reducing energy consumption and operational costs.

Green nanotechnology also offers enhanced safety and biocompatibility. Nanomaterials produced through biological routes are generally capped with natural biomolecules, which improve their stability and reduce potential toxicity compared to chemically synthesized nanoparticles. This makes them more suitable for applications involving direct contact with drinking water and biological systems. Furthermore, the use of green synthesis supports waste valorization by utilizing agricultural and plant waste, thereby contributing to circular economy principles and sustainable resource management.

Finally, green nanotechnology provides high efficiency in environmental applications, particularly in water purification. Green-synthesized nanomaterials exhibit strong antimicrobial, adsorptive, and photocatalytic properties, making them highly effective in removing heavy metals, organic pollutants, and pathogens from water. Their multifunctional nature, combined with sustainability and affordability, makes green nanotechnology a powerful tool for addressing water quality challenges in developing regions.

Challenges and Limitations of Green Nanotechnology

Despite its significant potential in water purification and environmental remediation, green nanotechnology faces several technical, environmental, and practical challenges that limit its large-scale application. One of the major challenges is the lack of scalability. While green synthesis of nanomaterials is well-established at the laboratory level, producing nanoparticles in large, consistent quantities with uniform size, shape, and functionality remains difficult. Variations in biological sources such as plant extracts or microbial strains can lead to inconsistencies in nanoparticle characteristics, affecting their performance in real-world applications.

Another key limitation is the incomplete understanding of toxicity and environmental impact. Although green-synthesized nanomaterials are considered safer than chemically produced ones, their long-term effects on human health, aquatic ecosystems, and soil microorganisms are not fully known. Nanoparticles may still accumulate in the environment and enter food chains, potentially causing unforeseen ecological risks. This uncertainty highlights the need for extensive toxicological studies and environmental monitoring before widespread implementation.

Recovery and reuse of nanomaterials also present a significant challenge. Once released into water systems, many nanoparticles are difficult to separate efficiently, which may lead to secondary pollution and increased operational costs. Although magnetic nanoparticles like Fe_3O_4 offer easier recovery, not all nanomaterials possess such properties, limiting their practical use in large-scale water treatment systems. Furthermore, there is a lack of standardized regulations and policies governing the production, use, and disposal of green nanomaterials, particularly in developing countries. This regulatory gap creates challenges in ensuring safe and controlled application. Limited infrastructure, inadequate technical expertise, and low public awareness further hinder adoption in resource-constrained regions.

Overall, while green nanotechnology offers promising solutions for sustainable water

purification, addressing these challenges is essential for its safe, efficient, and large-scale implementation in the future.

Conclusion

Green synthesis of nanomaterials represents a significant advancement in the field of sustainable water purification, offering an eco-friendly and efficient alternative to conventional chemical and physical methods. By utilizing biological resources such as plant extracts, microorganisms, and agricultural waste, this approach minimizes the use of toxic chemicals and reduces environmental pollution while producing highly functional nanomaterials. These green-synthesized nanoparticles demonstrate strong capabilities in removing heavy metals, degrading organic pollutants, and eliminating pathogenic microorganisms from contaminated water, making them highly suitable for addressing complex water quality issues.

The integration of green nanotechnology into water treatment systems is particularly valuable for developing regions, where access to clean water and advanced purification technologies is limited. Its low cost, energy efficiency, and reliance on locally available biological materials make it a practical solution for decentralized and community-based water purification systems. However, despite its promising potential, challenges such as scalability, nanoparticle recovery, limited toxicity data, and lack of regulatory frameworks must be addressed to ensure safe and effective implementation. The green nanotechnology offers a sustainable pathway toward achieving safe drinking water and environmental protection. With continued research, technological innovation, and policy support, it has the potential to play a transformative role in meeting global water demands and supporting the goals of sustainable development.

Green synthesis of nanomaterials has emerged as a transformative and sustainable approach for addressing global water purification challenges, particularly in developing regions where conventional treatment technologies are often inaccessible or economically unfeasible. By replacing toxic chemicals and energy-intensive processes with biological resources such as plant extracts, microorganisms, and agricultural waste, this method aligns strongly with the principles of green chemistry and environmental sustainability. The resulting nanomaterials exhibit remarkable efficiency in removing heavy metals, degrading persistent organic pollutants, and eliminating pathogenic microorganisms, making them highly suitable for comprehensive water treatment applications.

One of the most significant contributions of green-synthesized nanomaterials lies in their multifunctionality. Unlike traditional adsorbents or disinfectants that target specific contaminants, these nanomaterials can simultaneously address multiple types of pollutants through adsorption, photocatalysis, and antimicrobial mechanisms. This integrated functionality enhances water purification efficiency while reducing the need for multiple treatment stages. Furthermore, their production from renewable biological sources supports waste valorization and circular economy practices, adding an additional layer of environmental and economic benefit.

Despite these advantages, the transition from laboratory research to real-world application remains a major challenge. Issues related to large-scale production, stability under environmental conditions, nanoparticle recovery, and potential ecological impacts require urgent attention. Moreover, the absence of standardized

regulatory frameworks and limited institutional capacity in developing countries hinder the safe and controlled deployment of nanotechnology-based water treatment systems. Addressing these challenges will require interdisciplinary collaboration among chemists, environmental scientists, engineers, and policymakers.

Future progress in this field is expected to focus on improving synthesis scalability, enhancing nanoparticle reusability, and developing hybrid systems that combine green nanomaterials with conventional filtration technologies. Such innovations could significantly improve treatment efficiency while ensuring safety and affordability. With continued research and strategic implementation, green nanotechnology has the potential to become a cornerstone of sustainable water management systems, contributing directly to global efforts aimed at achieving universal access to clean and safe drinking water under the Sustainable Development Goals (SDG 6).

Future Prospects

The future of green synthesis of nanomaterials for water purification is highly promising, particularly in the context of increasing global water scarcity and pollution challenges. One of the key future directions is the development of scalable and standardized synthesis methods. Current research is largely laboratory-based, so advancing toward industrial-scale production with consistent nanoparticle size, shape, and functionality is essential for real-world applications. This will require improved control over biological synthesis conditions and better understanding of reaction mechanisms.

Another important prospect is the integration of green nanomaterials into hybrid water treatment systems. Combining nanoparticles with conventional technologies such as membrane filtration, activated carbon, and bio-sand filters can significantly enhance pollutant removal efficiency while maintaining cost-effectiveness. These hybrid systems can also reduce membrane fouling and improve the lifespan of filtration units, making them more suitable for long-term use in developing regions.

Future research is also expected to focus on improving the safety, recyclability, and environmental compatibility of nanomaterials. The development of magnetic and recoverable nanoparticles, such as functionalized Fe_3O_4 -based systems, will allow easier separation and reuse, reducing secondary pollution risks. In addition, advanced coating and immobilization techniques may help prevent nanoparticle leakage into the environment.

Another emerging direction is the use of artificial intelligence (AI) and machine learning to optimize green synthesis processes. These technologies can help predict optimal biological sources, reaction conditions, and nanoparticle properties, thereby improving efficiency and reproducibility. Similarly, the use of locally available biomass in rural and agricultural communities can promote decentralized production systems, reducing dependence on industrial facilities.

Finally, policy development and regulatory frameworks will play a crucial role in the future expansion of green nanotechnology. Establishing safety standards, environmental guidelines, and quality control measures will ensure responsible use of nanomaterials. With continued innovation and interdisciplinary collaboration, green nanotechnology has the potential to become a cornerstone of sustainable water treatment solutions worldwide, especially in resource-limited and developing regions.

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