Review

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Review

Biocompatible Functional Nanostructures via Green Synthesis: Advances in Nanomedicine, Environmental, and Energy Applications

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Abstract

The development of biocompatible functional nanostructures has emerged as a key driver in advancing nanomedicine, environmental remediation, and sustainable energy technologies. However, conventional synthesis methods often rely on toxic reagents, hazardous solvents, and energy-intensive processes, raising significant concerns regarding environmental impact and biological safety. In this context, green synthesis has gained increasing attention as a sustainable alternative, utilizing biological systems, renewable resources, and environmentally benign solvents to produce functional nanomaterials. This mini-review provides a comprehensive overview of recent advances in the green synthesis of organic, inorganic, and hybrid nanostructures, highlighting their physicochemical properties and functional performance. Particular emphasis is placed on their applications in nanomedicine, including drug delivery, bioimaging, antimicrobial and anticancer therapies, and theranostic platforms. Additionally, their roles in environmental applications, such as pollutant degradation and water treatment, and in energy-related systems, including catalysis, solar energy conversion, and energy storage, are critically discussed. Despite significant progress, key challenges remain, including limited mechanistic understanding, reproducibility issues, scalability constraints, and uncertainties related to long-term toxicity and environmental impact. Addressing these limitations will be essential for the safe and large-scale implementation of green nanotechnology. Overall, the integration of green chemistry principles with advanced nanomaterial design offers a promising pathway toward the development of multifunctional, sustainable, and high-performance nanostructures capable of addressing global health, environmental, and energy challenges.

Keywords: green synthesis; biocompatible nanostructures; nanomedicine; drug delivery; bioimaging; environmental remediation; energy applications; theranostics

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1. Introduction

The rapid evolution of nanotechnology has enabled the design and fabrication of functional nanostructures with unprecedented control over size, morphology, and surface chemistry. These features confer unique physicochemical properties, including high surface-to-volume ratios, quantum confinement effects, and tunable reactivity, positioning nanomaterials at the forefront of innovation in nanomedicine, environmental remediation, and energy technologies [1–3].

In particular, nanomedicine has emerged as a transformative field, offering advanced solutions for targeted drug delivery, bioimaging, biosensing, and theranostic applications [4–6]. These approaches have significantly improved diagnostic accuracy and therapeutic efficiency, contributing to the development of personalized medicine.

Despite these advances, conventional methods for synthesizing nanostructures often rely on toxic chemicals, hazardous reducing agents, and energy-intensive processes, raising serious concerns

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regarding environmental sustainability and biological safety [7,8]. The presence of residual toxic reagents can compromise the applicability of nanomaterials in biomedical contexts, where strict safety requirements must be met.

In this context, green synthesis has emerged as a promising alternative, utilizing biological systems such as plant extracts, microorganisms, and biomolecules to produce nanomaterials under environmentally benign conditions [3,9]. These approaches not only reduce environmental impact but also enhance the biocompatibility and functional properties of the resulting nanostructures.

Beyond nanomedicine, green-synthesized nanomaterials have demonstrated significant potential in environmental and energy applications. In environmental systems, they are widely used for pollutant degradation, water purification, and antimicrobial treatments [9,10]. In the energy sector, nanostructured materials contribute to improved catalytic performance, solar energy conversion, and advanced energy storage systems [2,10].

Although substantial progress has been achieved, several challenges remain, including limited mechanistic understanding, reproducibility issues, and scalability constraints [3,8]. Addressing these challenges will be essential for translating green nanotechnology into practical and industrial applications.

In this mini-review, we provide an overview of recent advances in green-synthesized biocompatible functional nanostructures, with emphasis on their applications in nanomedicine, environmental remediation, and energy systems, as well as current challenges and future perspectives.

2. Green Synthesis of Functional Nanostructures

The increasing concern over environmental sustainability and biological safety has driven the transition from conventional physicochemical synthesis methods toward greener and more sustainable approaches for the production of functional nanostructures. Traditional synthesis routes often involve toxic reagents, hazardous solvents, and high-energy consumption, which not only generate environmentally harmful byproducts but also compromise the biocompatibility of the resulting nanomaterials [8,11]. In contrast, green synthesis offers an eco-friendly alternative by employing renewable resources, benign reaction conditions, and energy-efficient processes, while maintaining control over nanoparticle size, morphology, and functionality [3,12].

Green synthesis strategies are generally based on three main principles: the use of biological systems as reducing and stabilizing agents, the replacement of toxic solvents with environmentally benign alternatives, and the adoption of low-energy or hybrid synthesis techniques [2,13]. These approaches not only reduce environmental impact but also introduce intrinsic functionalization, which is particularly advantageous for biomedical applications [4,14].

2.1. Biological Routes

Biological synthesis has emerged as a cornerstone of green nanotechnology, utilizing naturally derived biomolecules and living organisms to mediate nanoparticle formation [3,10]. Among these, plant-mediated synthesis is one of the most widely explored methods due to its simplicity, scalability, and cost-effectiveness [12,15]. Plant extracts contain a diverse array of phytochemicals, such as flavonoids, polyphenols, terpenoids, and alkaloids, which act simultaneously as reducing and capping agents [14,15]. This dual role enables the formation of stable nanostructures without the need for additional chemical stabilizers, thereby enhancing biocompatibility [4].

Microbial synthesis, involving bacteria, fungi, and algae, provides an alternative approach with greater control over nanoparticle size and morphology [16,17]. These organisms can facilitate both intracellular and extracellular synthesis through enzymatic reactions and metabolic pathways [18]. Despite their advantages in producing well-defined nanostructures, microbial methods often require controlled growth conditions, longer synthesis times, and more complex downstream processing, which may limit their large-scale applicability [16].

Enzyme-assisted synthesis represents a more controlled biological route, where specific enzymes catalyze nanoparticle formation under mild conditions [19,20]. This approach offers high selectivity and reproducibility, allowing precise tuning of nanoparticle properties. However, the high cost of enzymes and challenges related to their stability may restrict widespread implementation [19].

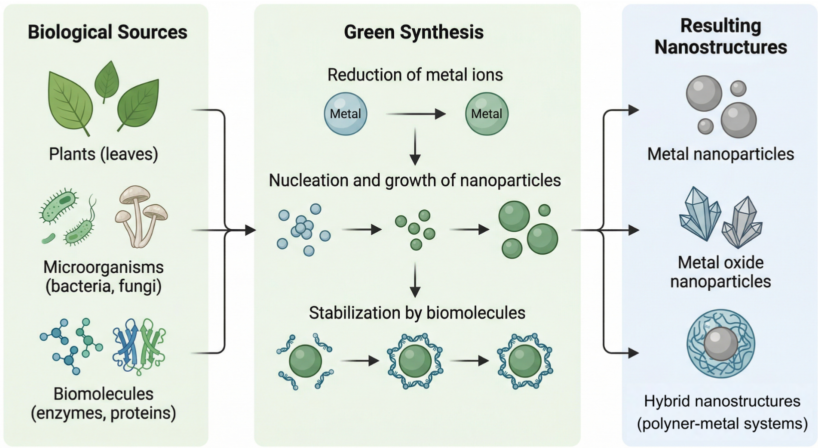

Figure 1. Schematic illustration of green synthesis of functional nanostructures. Biological sources, including plants, microorganisms, and biomolecules, act as reducing and stabilizing agents, enabling the formation of nanostructures under environmentally benign conditions. The process involves the reduction of metal ions, followed by nucleation and growth, and stabilization through biomolecular capping. These mechanisms lead to the formation of biocompatible metal, metal oxide, and hybrid nanostructures with tunable physicochemical properties suitable for diverse applications.

2.2. Green Solvents and Low-Energy Techniques

The selection of solvents plays a critical role in determining the sustainability and safety of nanomaterial synthesis [21]. Water is the most commonly used green solvent due to its non-toxic nature, abundance, and compatibility with biological systems. Nevertheless, emerging solvent systems such as ionic liquids and deep eutectic solvents have attracted significant attention owing to their unique physicochemical properties, including low volatility, high thermal stability, and tunable polarity [22,23].

These solvents can enhance nanoparticle stability, control nucleation processes, and enable the synthesis of complex nanostructures under relatively mild conditions [22]. However, their large-scale application requires careful evaluation of toxicity, cost, and recyclability [23].

In parallel, low-energy synthesis techniques have been developed to reduce energy consumption and improve process efficiency. Microwave-assisted synthesis enables rapid and uniform heating, significantly shortening reaction times and improving nanoparticle homogeneity [24]. Ultrasound-assisted methods rely on acoustic cavitation to promote nucleation and dispersion, leading to better control over particle size and morphology [25]. Additionally, photochemical and light-driven processes offer sustainable alternatives by utilizing renewable energy sources, further reducing the environmental footprint of nanomaterial production [26].

2.3. Hybrid and Multifunctional Nanostructures

The development of hybrid and multifunctional nanostructures represents a key advancement in green nanotechnology [27]. By integrating organic and inorganic components, these systems can combine multiple functionalities—such as optical, magnetic, catalytic, and biological properties—within a single platform [28].

Green synthesis approaches have been successfully applied to the fabrication of such hybrid systems, often using biopolymers, proteins, or polysaccharides as templates and stabilizing matrices [29,30]. These materials not only improve nanoparticle stability but also introduce additional functional groups that facilitate further modification and application [30].

Multifunctional nanostructures are particularly relevant for complex applications that require synergistic effects. In nanomedicine, they enable the development of theranostic platforms that combine imaging and therapy [4]. In environmental applications, they can simultaneously perform

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adsorption and catalytic degradation of pollutants [28]. In energy systems, hybrid nanostructures contribute to improved catalytic efficiency and charge transfer [2].

Despite these advances, challenges remain in achieving precise control over the structure-function relationship in hybrid systems, as well as ensuring reproducibility and scalability [3,8]. Addressing these limitations will be essential for translating green-synthesized multifunctional nanostructures into practical applications.

3. Applications

The application of green-synthesized biocompatible functional nanostructures has expanded significantly across multiple scientific and technological domains [2,3]. Owing to their tunable physico-chemical properties, intrinsic surface functionalization, and reduced toxicity, these nanomaterials have demonstrated remarkable versatility in nanomedicine, environmental remediation, and energy-related systems [4,10]. The integration of green synthesis principles further enhances their sustainability and suitability for practical applications [7].

As illustrated in Figure 2, green-synthesized nanostructures enable a wide range of multifunctional applications. In nanomedicine, they support advanced diagnostic and therapeutic platforms, including targeted drug delivery, bioimaging, biosensing, gene delivery, and theranostic cancer therapy [5,6]. In environmental systems, these nanomaterials contribute to water purification, antimicrobial treatment, pollutant degradation, air pollutant removal, and heavy metal removal through adsorption and catalytic processes [9,13]. In energy applications, they play a critical role in solar energy conversion, hydrogen production, and the development of high-performance energy storage systems [1,2].

The convergence of these applications highlights the interdisciplinary nature of sustainable nanotechnology and its potential to address global challenges in healthcare, environmental protection, and clean energy [7,8]. In the following subsections, the specific mechanisms and roles of green-synthesized nanostructures in each domain are discussed in detail.

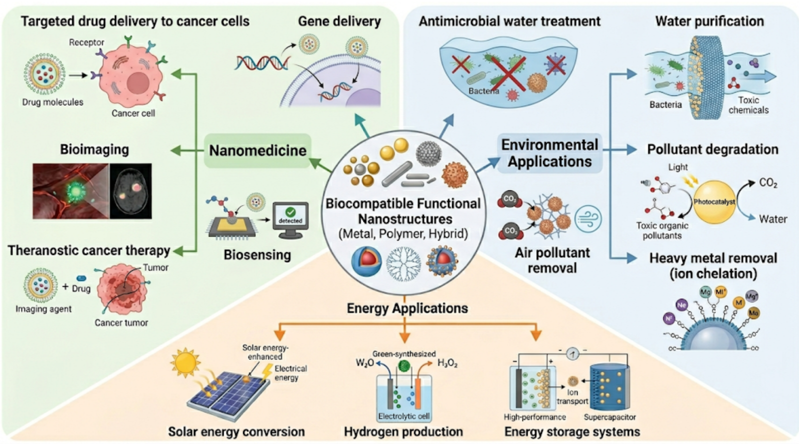

Figure 2. Multifunctional applications of green-synthesized biocompatible functional nanostructures across nanomedicine, environmental, and energy domains. In nanomedicine, these nanostructures enable targeted drug delivery, bioimaging, biosensing, gene delivery, and theranostic cancer therapy. In environmental applications, they contribute to water purification, antimicrobial treatment, pollutant degradation, air pollutant removal, and heavy metal removal via ion chelation. In the energy sector, they support solar energy conversion, hydrogen production, and advanced energy storage systems. The figure highlights the versatility and interdisciplinary impact of sustainable nanostructures in addressing global health, environmental, and energy challenges.

4. Applications in Nanomedicine

The application of biocompatible functional nanostructures in nanomedicine has significantly advanced the development of innovative diagnostic and therapeutic strategies [3,4]. Green-synthesized nanomaterials, in particular, offer unique advantages due to their reduced toxicity, intrinsic surface functionalization, and enhanced compatibility with biological systems [8,14]. These features make

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them highly suitable for biomedical applications, where safety, efficiency, and targeted functionality are critical. As a result, sustainable nanotechnology has become an important driver in the evolution of next-generation nanomedical platforms [7,13].

4.1. Drug Delivery and Controlled Release

Nanostructured systems have transformed conventional drug delivery approaches by enabling targeted transport and controlled release of therapeutic agents [4,5]. Biocompatible nanoparticles synthesized via green methods often possess surface functional groups derived from biological precursors, which facilitate drug loading and improve cellular uptake [3,14].

Targeted delivery can be achieved through passive or active mechanisms. Passive targeting is primarily based on the enhanced permeability and retention (EPR) effect, which allows nanoparticles to accumulate in tumor tissues due to their leaky vasculature [31]. However, the heterogeneity of the EPR effect across different tumor types remains a limitation, necessitating the development of more precise targeting strategies [32].

Active targeting involves functionalization of nanostructures with ligands such as antibodies, peptides, or small molecules that selectively bind to overexpressed receptors on diseased cells [33]. Green synthesis offers an advantage in this context by enabling surface functionalization during nanoparticle formation, reducing the need for post-synthetic chemical modifications [14].

Controlled release systems based on stimuli-responsive nanostructures have further improved therapeutic efficiency [34]. These systems respond to internal stimuli such as pH, redox conditions, and enzymatic activity, or external triggers such as temperature, light, and magnetic fields. Such responsiveness enables site-specific drug release, minimizing systemic toxicity and enhancing therapeutic outcomes [34].

4.2. Bioimaging and Biosensing

Nanostructures have played a crucial role in improving the sensitivity and resolution of imaging and biosensing technologies [3,4]. Materials such as gold nanoparticles, quantum dots, and magnetic nanostructures exhibit unique optical and magnetic properties that make them ideal for use as contrast agents and signal amplifiers [6].

Green synthesis contributes to the development of safer imaging agents by reducing cytotoxicity and improving colloidal stability in physiological environments [8]. In particular, biologically derived capping agents can enhance circulation time and reduce immune recognition, thereby improving in vivo imaging performance [14].

In biosensing applications, functional nanostructures enable rapid and highly sensitive detection of biomolecules, pathogens, and disease markers [3,6]. Their high surface area and tunable surface chemistry allow for selective interaction with target analytes, generating measurable optical, electrochemical, or magnetic signals. The integration of green-synthesized nanomaterials into biosensors supports the development of portable and point-of-care diagnostic devices [4].

4.3. Antimicrobial and Anticancer Applications

Green-synthesized nanomaterials have demonstrated significant potential in antimicrobial and anticancer therapies [3,4]. Metallic nanoparticles, particularly silver, gold, and zinc oxide, exhibit strong antimicrobial activity against a wide range of pathogens [35].

The antimicrobial mechanisms are generally associated with the generation of reactive oxygen species (ROS), disruption of cell membranes, and interference with intracellular processes [35]. Importantly, the presence of bioactive compounds from biological synthesis routes can enhance these effects, leading to synergistic antimicrobial activity [14].

In cancer therapy, nanostructures enable targeted delivery of chemotherapeutic agents and can also act as therapeutic agents through mechanisms such as photothermal therapy, photodynamic therapy, and ROS-mediated apoptosis [5,34]. However, challenges related to selectivity, biodistribution, and long-term toxicity remain critical barriers to clinical translation [32].

4.4. Theranostic Platforms

Theranostics represents a rapidly evolving field that integrates diagnostic and therapeutic functionalities within a single nanostructured platform [3,36]. These systems enable real-time monitoring of disease progression and treatment response, supporting the development of personalized medicine [33].

Biocompatible hybrid nanostructures are particularly well-suited for theranostic applications, as they can incorporate imaging agents, drug delivery systems, and targeting ligands into a unified architecture [6]. Green synthesis approaches facilitate the integration of these components while minimizing toxicity and improving overall system stability [8,14].

Recent advances have demonstrated the potential of multifunctional nanostructures in applications such as image-guided therapy, combined chemo-photothermal treatments, and multimodal imaging [34,36]. Despite these promising developments, challenges related to regulatory approval, large-scale production, and clinical validation remain to be addressed [32].

5. Environmental Applications

Green-synthesized biocompatible nanostructures have emerged as highly effective materials for addressing critical environmental challenges, particularly in water treatment, pollutant degradation, and remediation of contaminated ecosystems [3,10]. Their high surface area, tunable surface chemistry, and catalytic properties enable efficient interaction with a wide range of contaminants, including organic pollutants, heavy metals, and emerging contaminants such as pharmaceuticals and microplastics [4,9].

5.1. Pollutant Degradation and Photocatalysis

Photocatalytic nanomaterials play a central role in the degradation of organic pollutants in water and air [3,37]. Metal oxide nanostructures, such as titanium dioxide (TiO_2) and zinc oxide (ZnO), are widely used due to their strong oxidative capabilities under light irradiation [37]. Green synthesis methods enhance the sustainability of these materials while often introducing surface functional groups that improve photocatalytic efficiency [9,10].

Under light exposure, these nanostructures generate reactive oxygen species (ROS), including hydroxyl radicals and superoxide ions, which can effectively degrade dyes, pesticides, and pharmaceutical residues into less harmful compounds [37]. The use of green-synthesized nanomaterials not only reduces the environmental impact of their production but also improves their stability and reusability, which are critical for large-scale applications [3].

Recent studies have also explored the incorporation of dopants and the development of hybrid nanostructures to extend light absorption into the visible region, thereby enhancing photocatalytic performance under solar irradiation [38]. These advancements are essential for the development of energy-efficient and sustainable remediation technologies [37].

5.2. Heavy Metal Removal and Water Treatment

The removal of heavy metals from water systems is a major environmental concern due to their toxicity, persistence, and bioaccumulation [3,39]. Biocompatible nanostructures synthesized via green routes have demonstrated excellent adsorption capacities for metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}), and arsenic (As^{3+}) [9,10].

The effectiveness of these nanomaterials is largely attributed to their high surface area and the presence of functional groups, such as hydroxyl, carboxyl, and amine groups, which facilitate strong interactions with metal ions [39]. Biosynthesized nanoparticles and nanocomposites, particularly those incorporating biopolymers or carbon-based materials, exhibit enhanced adsorption performance and selectivity [3,4].

In addition to adsorption, some nanostructures can reduce or transform toxic metal ions into less harmful forms through catalytic processes [39]. The integration of adsorption and catalytic functionalities in a single material further enhances the efficiency of water treatment systems [9].

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5.3. Multifunctional Nanomaterials for Environmental Remediation

The development of multifunctional nanostructures represents a significant advancement in environmental applications [3,4]. These systems are capable of performing multiple tasks simultaneously, such as adsorption, catalytic degradation, and antimicrobial activity, making them highly effective for complex environmental systems [9].

Green synthesis plays a key role in enabling the fabrication of such multifunctional materials, often through the use of biological templates or hybridization strategies [10]. For example, nanocomposites combining metal oxides with carbon-based materials or biopolymers can exhibit synergistic effects, leading to improved performance compared to single-component systems [3,39].

Moreover, the biocompatibility and reduced toxicity of green-synthesized nanomaterials minimize secondary environmental risks, which is particularly important for applications involving direct interaction with natural ecosystems [10,14].

Despite these promising developments, several challenges remain, including the recovery and reuse of nanomaterials after treatment, potential ecotoxicological effects, and the scalability of green synthesis methods [39]. Addressing these issues will be essential for the practical implementation of nanotechnology-based environmental solutions.

6. Energy Applications

The growing global demand for clean and sustainable energy has accelerated the development of advanced nanomaterials with enhanced catalytic, electronic, and structural properties [1,2]. In this context, green-synthesized biocompatible nanostructures have emerged as promising candidates for a wide range of energy-related applications, including catalysis, solar energy conversion, and energy storage systems [3,4]. Their environmentally friendly production, combined with tunable physicochemical characteristics, makes them particularly attractive for next-generation energy technologies [9,10].

6.1. Catalysis for Energy Conversion

Nanostructured materials play a crucial role in catalytic processes associated with energy conversion, such as hydrogen production, fuel cells, and carbon dioxide reduction [1,2]. Green-synthesized nanoparticles, particularly metal and metal oxide nanostructures, exhibit high catalytic activity due to their large surface area and abundant active sites [3,9].

In hydrogen production, nanocatalysts are widely used in water splitting reactions, where they facilitate the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) [40]. Green synthesis methods can produce catalysts with controlled morphology and surface functionality, improving catalytic efficiency while minimizing environmental impact [10].

Similarly, in fuel cell technologies, nanomaterials are employed as electrocatalysts to enhance reaction kinetics and reduce energy losses [41]. The use of biocompatible and sustainably produced nanostructures contributes to the development of safer and more cost-effective catalytic systems [4].

6.2. Solar Energy Conversion

Nanostructured materials have significantly improved the performance of solar energy conversion systems, including photovoltaic devices and photocatalytic systems [2,42]. Green-synthesized nanomaterials can be used as light absorbers, charge transport materials, or catalytic components in solar-driven processes [3,4].

In photovoltaic applications, nanostructures such as quantum dots, metal oxides, and hybrid nanocomposites enhance light absorption and charge separation, leading to improved energy conversion efficiency [38]. The use of green synthesis routes reduces the environmental footprint of these materials and supports the development of sustainable solar technologies [10].

Photocatalytic systems for solar fuel generation, such as hydrogen production and carbon dioxide reduction, also benefit from green-synthesized nanomaterials [37,38]. These systems utilize solar energy to drive chemical reactions, offering a renewable pathway for fuel production [1].

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6.3. Energy Storage Systems

Energy storage technologies, including batteries and supercapacitors, are essential for the efficient utilization of renewable energy sources [43,44]. Nanostructured materials have been extensively explored for these applications due to their high surface area, short diffusion paths, and enhanced electrochemical properties [43].

Green-synthesized nanomaterials, particularly carbon-based materials, metal oxides, and hybrid nanocomposites, have demonstrated excellent performance in energy storage devices [3,4]. In lithium-ion batteries, nanostructured electrodes improve charge capacity, cycling stability, and rate performance [43]. In supercapacitors, these materials contribute to high power density and rapid charge-discharge cycles [44].

The incorporation of biocompatible and sustainably produced nanomaterials into energy storage systems not only enhances performance but also reduces environmental impact, aligning with the principles of green energy technologies [10].

Despite significant progress, challenges remain in achieving large-scale production, long-term stability, and cost-effectiveness of green-synthesized nanomaterials for energy applications [44]. Further research is needed to optimize synthesis methods, improve material performance, and integrate these nanostructures into practical energy systems.

7. Challenges and Future Perspectives

Despite the significant progress achieved in the development of green-synthesized biocompatible nanostructures, several critical challenges remain that limit their translation from laboratory research to real-world applications. Addressing these limitations requires a deeper understanding of synthesis mechanisms, improved standardization, and integration of multidisciplinary approaches.

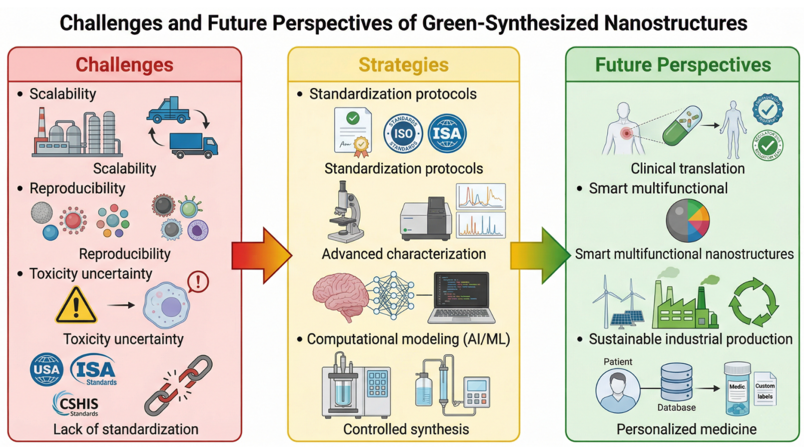

Figure 3. Key Challenges, Strategies, and Future Perspectives in Green-Synthesized Nanostructures.

7.1. Lack of Mechanistic Understanding

One of the major scientific gaps in green nanotechnology lies in the limited mechanistic understanding of biological synthesis processes [3,12]. Although plant extracts, microorganisms, and biomolecules are widely used as reducing and stabilizing agents, the exact pathways governing nucleation, growth, and stabilization of nanostructures remain poorly defined [8,13].

The complexity and variability of biological systems introduce significant uncertainty in controlling nanoparticle properties, such as size distribution, morphology, and surface chemistry [3]. This lack of predictability hampers reproducibility and limits the rational design of nanomaterials for specific applications [4]. Future research should focus on elucidating these mechanisms through advanced analytical techniques and computational modeling, enabling a more controlled and predictable synthesis process [12].

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7.2. Reproducibility and Standardization Issues

Reproducibility remains a major bottleneck in the field of green synthesis [8,13]. Variations in biological sources, extraction methods, and experimental conditions can lead to significant inconsistencies in nanoparticle characteristics [12]. This issue is particularly critical for biomedical applications, where precise control over material properties is essential [4].

Currently, there is a lack of standardized protocols for green synthesis, characterization, and performance evaluation [7]. The absence of universally accepted guidelines makes it difficult to compare results across studies and slows down technological advancement [3]. Establishing standardized methodologies and reporting frameworks will be essential to ensure reproducibility and facilitate regulatory approval [32].

7.3. Scalability and Industrial Translation

While green synthesis methods are often described as cost-effective and environmentally friendly, their scalability remains a significant challenge [3,8]. Biological processes may require longer reaction times, controlled conditions, and complex downstream processing, which can limit their feasibility for large-scale production [12,13].

Moreover, the transition from laboratory-scale synthesis to industrial manufacturing requires consistent quality, high yield, and economic viability [7]. The development of scalable green synthesis platforms, such as continuous-flow systems and bioreactor-based approaches, represents a promising direction for overcoming these limitations [4].

7.4. Toxicological and Environmental Uncertainties

Although green-synthesized nanomaterials are generally considered more biocompatible, comprehensive evaluation of their long-term toxicity and environmental impact is still lacking [13,45]. The interaction of nanomaterials with biological systems is highly complex and depends on multiple factors, including size, shape, surface chemistry, and dosage [45].

In addition, the fate and transformation of nanomaterials in environmental systems remain poorly understood [46]. Potential risks associated with bioaccumulation, persistence, and unintended ecological effects must be carefully assessed [45,46]. Future studies should adopt standardized toxicological frameworks and life cycle assessment approaches to ensure the safe implementation of nanotechnology [7].

7.5. Regulatory and Translational Barriers

The translation of nanomaterials into clinical and industrial applications is further hindered by regulatory challenges [32,45]. The lack of clear regulatory guidelines specific to green-synthesized nanomaterials complicates their approval process, particularly in the biomedical field [4].

Bridging the gap between academic research and industrial application will require closer collaboration between scientists, engineers, regulatory agencies, and industry stakeholders [46]. Developing clear regulatory pathways and validation protocols will be essential for accelerating commercialization [7].

7.6. Future Perspectives

Future research in green nanotechnology should focus on the integration of advanced characterization techniques, machine learning, and computational modeling to achieve predictive control over nanomaterial synthesis [3,12]. The development of smart and multifunctional nanostructures, capable of performing multiple tasks simultaneously, represents a key direction for next-generation applications [13].

In nanomedicine, efforts should be directed toward improving targeting efficiency, minimizing off-target effects, and enhancing clinical translation through robust preclinical validation [32,33]. In environmental and energy applications, the design of recyclable, stable, and high-performance nanomaterials will be critical for sustainable implementation [37,39].

Furthermore, the convergence of green chemistry, materials science, and biotechnology is expected to drive the development of innovative synthesis strategies and multifunctional systems [7].

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By addressing current challenges and leveraging interdisciplinary approaches, green-synthesized biocompatible nanostructures have the potential to play a transformative role in advancing sustainable technologies and improving global health [3,4].

8. Conclusion

Green synthesis has emerged as a powerful and sustainable strategy for the fabrication of biocompatible functional nanostructures, offering significant advantages over conventional physicochemical methods in terms of environmental impact, safety, and energy efficiency [3,7]. By leveraging biological systems such as plant extracts, microorganisms, and biomolecules, this approach enables the production of nanomaterials with intrinsic surface functionalization and enhanced biocompatibility, which are particularly advantageous for biomedical and environmental applications [4,12].

The versatility of green-synthesized nanostructures has been demonstrated across a wide range of domains, including nanomedicine, environmental remediation, and energy systems. In nanomedicine, these materials support advanced drug delivery systems, bioimaging, and theranostic platforms. In environmental applications, they contribute to pollutant degradation, water treatment, and ecosystem remediation. In energy-related systems, they enhance catalytic processes, solar energy conversion, and energy storage performance, highlighting their multifunctional potential [9,10].

Despite these promising developments, several challenges remain, including limited mechanistic understanding, reproducibility issues, scalability constraints, and concerns related to long-term toxicity and regulatory approval. Addressing these limitations will require interdisciplinary efforts combining advanced characterization techniques, computational modeling, and standardized methodologies to enable precise control over nanomaterial synthesis and performance [13,45].

Looking forward, the integration of green chemistry principles with emerging technologies such as machine learning, synthetic biology, and nanomanufacturing is expected to accelerate the development of next-generation nanomaterials. By overcoming current barriers and fostering collaboration between academia, industry, and regulatory bodies, green-synthesized biocompatible nanostructures have the potential to play a transformative role in advancing sustainable technologies and improving global health outcomes.

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