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Prospective applications of nanoparticles produced via green synthesis

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Abstract
The production of nanoparticles has emerged as a vital study domain owing to its distinctive features and uses across several domains, including medicine, electronics, and environmental science. Conventional nanoparticle production methods, including physical and chemical techniques, can provide considerable environmental and health risks owing to the utilisation of harmful substances and elevated energy demands. The green synthesis of nanoparticles provides a more eco-friendly and sustainable option. This approach employs biological organisms, including plants, bacteria, fungus, and algae, to synthesise nanoparticles, therefore minimising the reliance on hazardous chemicals and severe physical conditions. This work presents a thorough review of the green synthesis of nanoparticles, emphasising the diverse biological techniques utilised, the types of nanoparticles generated, and the numerous factors influencing their synthesis. The potential uses of green-synthesized nanoparticles across several sectors are examined, with the obstacles and future prospects of this environmentally friendly technique.

Keywords: Nanoparticle synthesis, green-synthesized nanoparticles, medicine, electronics

Introduction
Nanotechnology, defined as the manipulation of matter at the nanoscale (1-100 nm), has garnered significant scientific and industrial interest due to the extraordinary properties exhibited by nanoparticles [1]. These nanoscale particles possess distinct optical, magnetic, and electrical characteristics, which have made them highly beneficial across various domains, including medicine, electronics, and the chemical industry [2], [3]. Conventional nanoparticle synthesis methods primarily rely on physical and chemical techniques. While these methods are effective, they often present substantial environmental and health hazards due to the use of toxic chemicals, high temperatures, and excessive energy consumption [4]. This has led to an increased focus on developing sustainable and eco-friendly synthesis techniques, giving rise to the concept of green nanotechnology [5], [6].

Approaches Involved in Nanoparticle Synthesis
Nanoparticle synthesis is typically classified into two main approaches: the top-down and bottom-up techniques. The top-down approach focuses on reducing bulk materials to the nanoscale through physical or mechanical methods, including grinding, sputtering, and laser ablation [7], [8]. This method often results in particles with non-uniform shapes and sizes due to physical limitations [9]. Conversely, the bottom-up approach involves the self-assembly of nanoparticles from atomic or molecular precursors through chemical or biological processes [10]. This method allows for better control over the particle size, shape, and surface properties, making it advantageous for specific applications [11], [12].

Types of Nanoparticles Synthesised and Methods
Green synthesis methods have been employed to produce various types of nanoparticles, each possessing distinct properties and a wide range of applications:

1. **Metallic Nanoparticles:** These include silver, gold, copper, and palladium nanoparticles. Silver nanoparticles, in particular, exhibit strong antimicrobial properties and are extensively utilised in medical and antimicrobial applications [13].
2. **Metal Oxide Nanoparticles:** Common examples include zinc oxide and titanium dioxide nanoparticles. These nanoparticles are utilised in applications such as sunscreens, cosmetics, and environmental remediation [14].
3. **Alloy Nanoparticles:** Alloy nanoparticles, formed by combining different metals, can exhibit enhanced properties like improved catalytic activity and electrical conductivity, making them suitable for applications in catalysis and electronics [15].

Magnetic Nanoparticles: Nanoparticles such as iron oxide is widely used in medical imaging, targeted drug delivery, and magnetic data storage systems due to their unique magnetic properties [16].

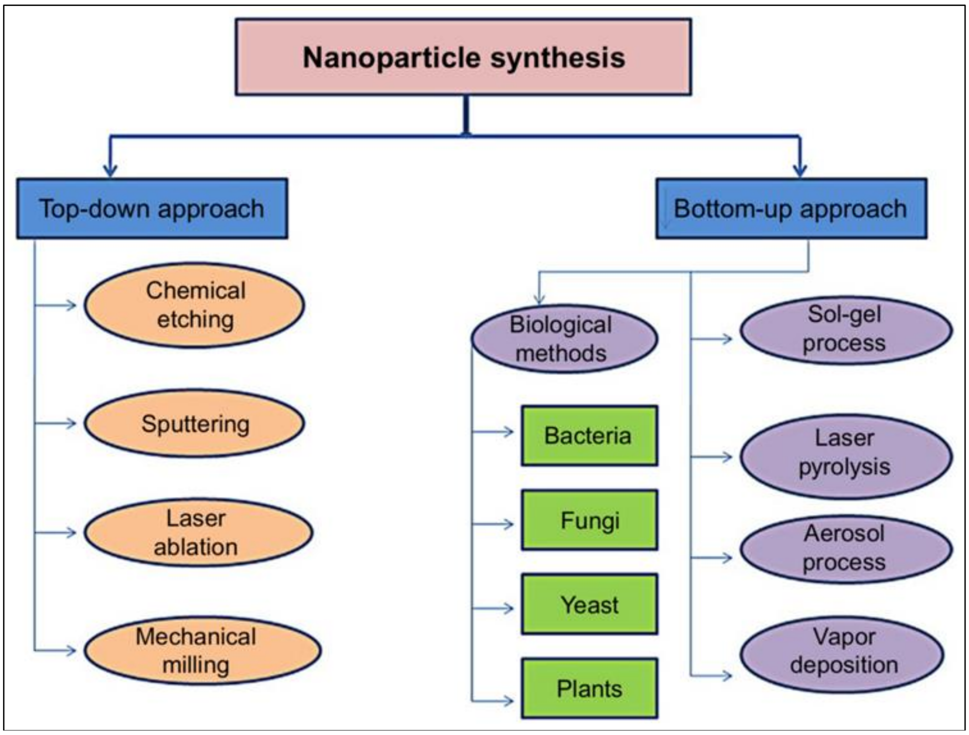

Fig 1: Different types of processes for the synthesis of nanoparticles.

The physical approach to nanoparticle generation encompasses several widely used methods, including laser ablation, high-energy ball milling (HEBM), electrospraying, evaporation-condensation, and laser pyrolysis [17]. Additionally, physical techniques such as arc discharge, metal sputtering, atomisation, and annealing are employed to synthesize nanoparticles [18]. These physical methods are advantageous over chemical techniques due to their ability to produce uncontaminated thin films and ensure uniform nanoparticle distribution [19].

A notable example is the synthesis of silver nanoparticles using a small ceramic heater. In this method, rapid cooling of vapour, caused by a steep temperature gradient near the heater surface, promotes the formation of small, high-concentration nanoparticles. This technique is especially useful for long-term studies on inhalation toxicity and nanoparticle measurement calibration [20].

Another method, laser ablation, involves the subdivision of metallic bulk materials in solution. This technique has been extensively used for synthesising silver nanoparticles, where factors such as laser wavelength, pulse duration (ranging from femtoseconds to nanoseconds), laser fluence, ablation time, and the characteristics of the liquid medium (with or without surfactants) play a significant role in determining the size and properties of the nanoparticles [21]. One of the key advantages of laser ablation is the ability to generate pure and uncontaminated metal colloids, making it ideal for applications requiring high purity [22].

Green Synthesis of Nanoparticles

Green synthesis of nanoparticles is a **bottom-up approach** that employs biological entities to reduce metal ions to nanoparticles. This sustainable method utilizes natural reducing and stabilizing agents found in plants, bacteria, fungi, and algae, offering an eco-friendly alternative to traditional chemical methods [23]. Biological methods for nanoparticle synthesis include:

1. **Bacteria-Mediated Synthesis:** Bacteria are extensively studied for their ability to synthesize nanoparticles. Enzymes present in bacterial cells reduce metal ions (e.g., Ag^{+}, Au^{3+}, and Pd^{2+}) to their respective nanoparticles. This process is simple, conducted at ambient temperature and pressure, and does not require toxic chemicals [24]. For example, *Escherichia coli* has been used to synthesize gold nanoparticles with significant catalytic activity [25].
2. **Fungi-Mediated Synthesis:** Fungi can tolerate and accumulate large amounts of metals, facilitating the reduction of metal ions through extracellular enzymes. Filamentous fungi such as *Aspergillus* and *Fusarium* have been particularly effective in synthesizing nanoparticles [26]. This method offers benefits such as ease of handling, large-scale production potential, and control over particle morphology. For instance, the fungus *Fusarium oxysporum* has been employed to synthesize silver nanoparticles with strong antimicrobial properties [27].
3. **Algae-Mediated Synthesis:** Algae have attracted interest due to their rapid growth rates and capacity to accumulate metals. Bioactive compounds in algae aid in the reduction and stabilization of nanoparticles [28]. For example, the green alga *Chlorella vulgaris* has been used to synthesize gold nanoparticles, which are subsequently applied in biomedical fields [29].
4. **Plant-Mediated Synthesis:** Plant extracts, rich in phytochemicals such as alkaloids, flavonoids, terpenoids, and phenolics, act as reducing and stabilizing agents in nanoparticle synthesis. This method is simple, cost-effective, and scalable for industrial applications [30]. Various plants, including *Azadirachta indica* (neem),

Ocimum sanctum (tulsi), and *Camellia sinensis* (green tea), have been used for nanoparticle synthesis. For instance, neem leaf extract has been utilized to produce silver nanoparticles with significant antibacterial activity [31].

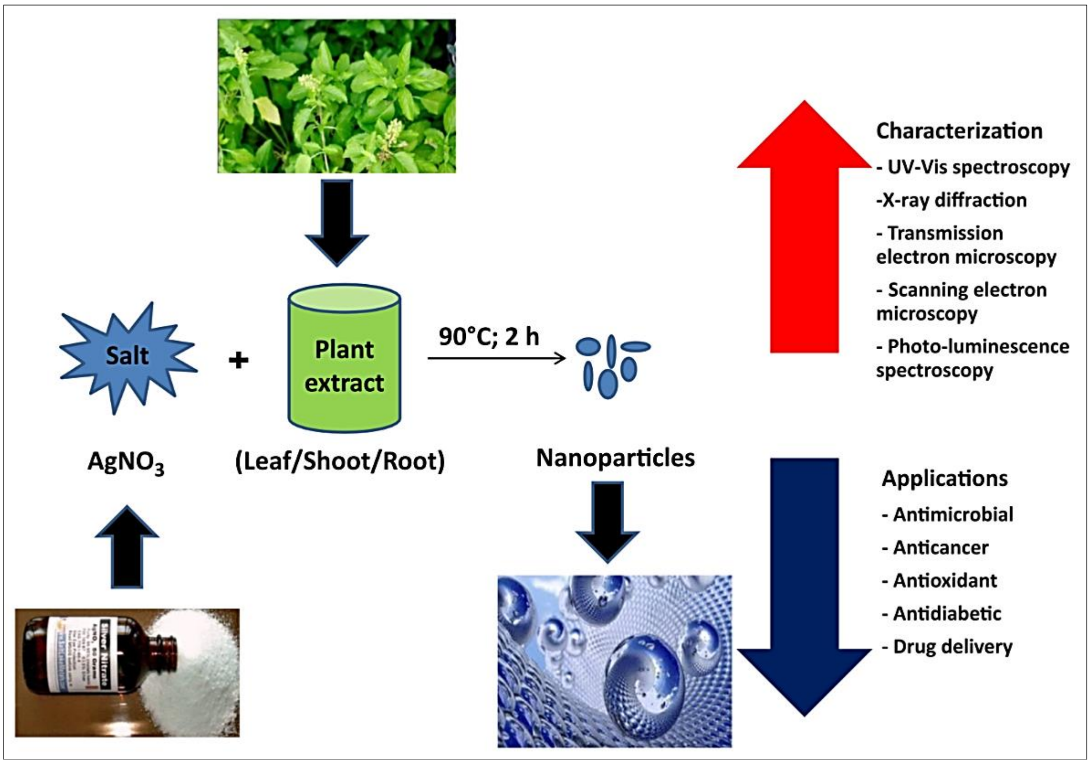

Fig 2: Schematic diagram depicting green synthesis of silver nanoparticles.

Table 1: A list of nanoparticles (with size details) synthesized using microbes and plant extracts

SN	NP	Source	Size
1.	Silver	Reetha and Shikakai leaves extract	~30 nm
2.	Fe NPs	Eucalyptus leaf extract	95±5nm
3.	Copper	Coccinia grandis fruit extract	40-50 nm
4.	Selenium	Escherichia coli, Pseudomonas aeruginosa, Methicillin-resistant Staphylococcus aureus, and S. aureus	90-150 nm
5.	Fe-NPs	Eucalyptus leaves	70±20 nm
6.	Gold	Cladosporium cladosporioides fungus isolated from seaweed	Within 100 nm
7.	Selenium	Vibrio natriegensas	136±31 nm
8.	Silver	Pongamia pinnata	5-15 nm (small) and 22-55 nm (large)
9.	Gold	Trichosporon montevideense	53-12 nm
10.	Zinc oxide	Rosa canina	less than 50 nm

The kinetics of plant-mediated nanomaterial synthesis are significantly faster compared to other biosynthetic methods, closely rivaling chemical nanoparticle synthesis [32]. Various medicinal plants have been employed to synthesize silver nanoparticles, which have found extensive applications in the pharmaceutical and biological sectors. For example, plants such as *Oryza sativa* (rice), *Helianthus annus* (sunflower), *Saccharum officinarum* (sugarcane), *Sorghum bicolor* (sorghum), *Aloe vera*, *Zea mays* (maize), *Basella alba*, and *Capsicum annuum* (chili) have demonstrated effectiveness in nanoparticle synthesis [33].

The aqueous extract of *Alternanthera dentata* has facilitated the rapid synthesis of silver nanoparticles (50-100 nm) within 10 minutes, exhibiting antibacterial activity against multiple bacterial strains [34]. Similarly, gold nanoparticles (20-25 nm) with diverse shapes were synthesized using *Cymbopogon citratus* (lemongrass) leaf extract, enhancing the predation efficiency of the copepod *Mesocyclops aspericornis* against mosquito larvae responsible for malaria and dengue transmission [35]. Copper oxide nanoparticles were synthesized through a colloid-thermal process using *Euphorbia nivulia*, where antibacterial properties were attributed to terpenoids and peptides present in the plant latex [36]. *Aloe vera* extract was used to synthesize indium oxide nanoparticles, which were characterized for their structural, morphological, and optical properties [37].

Additionally, zinc oxide nanoparticles with a hexagonal wurtzite structure were synthesized from *Sedum alfredii*, with an average size of 53.7 nm [38]. Iron oxide nanoparticles were synthesized using alfalfa (*Medicago sativa*), where varying the pH controlled the size of aggregates. The size ranged from 1-10 nm, with optimal pH conditions yielding particles between 1-4 nm [39].

Mechanism of Green Synthesis:

The green synthesis of nanoparticles involves a series of key steps, including the preparation of the biological extract, reduction of metal ions, and stabilization of the synthesized nanoparticles. While the exact mechanism varies depending on the biological source and the type of nanoparticles, the process generally follows the steps below:

1. **Preparation of Extract:** The biological material (plant, bacteria, fungi, or algae) is processed to extract active compounds. This typically involves washing, drying, and grinding the material, followed by solvent extraction to obtain bioactive compounds such as alkaloids, flavonoids, terpenoids, and phenolics [40]. These compounds act as both reducing and stabilizing agents.
2. **Reduction of Metal Ions:** The biological extract is mixed with a solution of metal ions. The active compounds in the extract reduce the metal ions to their zero-valent state, leading to the nucleation and formation of nanoparticles [41]. The efficiency of this reduction process is influenced by various factors, including pH, temperature, metal ion concentration, and reaction time [42]. For instance, optimal pH conditions can significantly enhance the reduction rate and particle uniformity.
3. **Stabilization of Nanoparticles:** The phytochemicals present in the biological extract also play a critical role in stabilizing the nanoparticles, preventing aggregation and ensuring the nanoparticles maintain their desired size and morphology [43]. This stabilization is achieved through the formation of a protective layer around the nanoparticles, which enhances their stability in different environments and applications [44].

Factors Influencing Green Synthesis

The green synthesis of nanoparticles is significantly influenced by various parameters that must be precisely controlled to achieve nanoparticles with the desired size, shape, and properties. Among these factors, pH plays a critical role in the process. The pH of the reaction medium affects the ionization of the reducing agents in the biological extract and the solubility of metal ions. Changes in pH can alter the reduction process and impact the morphology and size of the resulting nanoparticles. For instance, an optimal pH promotes uniform particle formation, while an imbalanced pH may lead to irregular shapes and sizes [42].

Temperature is another crucial factor that directly affects the reaction kinetics. Elevated temperatures can accelerate the reduction of metal ions, leading to faster nanoparticle formation and generally smaller particle sizes. However, excessively high temperatures can cause the nanoparticles to aggregate, compromising their stability [42]. Therefore, maintaining an optimal temperature range is essential to balance the rate of reaction and prevent unwanted agglomeration.

The reaction time also influences nanoparticle synthesis by affecting their growth and stabilization. Short reaction times may result in incomplete formation, while prolonged reactions allow for further growth, potentially leading to larger particles. Careful monitoring of the reaction duration helps in achieving consistent and controlled nanoparticle sizes [47].

The concentration of metal ions in the solution determines the rate of nucleation and subsequent growth of nanoparticles. A higher concentration may enhance the rate of particle formation but can also lead to increased aggregation if not properly balanced. Conversely, too low a concentration may result in insufficient nucleation, leading to incomplete synthesis. Optimal metal ion concentration is essential to obtain uniform particle size distribution and prevent clustering [60].

Finally, the concentration of the biological extract is vital for providing sufficient reducing and stabilizing agents. The availability of bioactive compounds in the extract influences both the reduction process and nanoparticle stabilization. An inadequate amount of extract may hinder the reduction of metal ions, while an excess can lead to over-reduction or agglomeration. By optimizing the concentration of the biological extract, it is possible to enhance the efficiency of nanoparticle formation and achieve better control over their structural properties [43].

Together, these factors—pH, temperature, reaction time, and concentrations of both metal ions and biological extracts—play interconnected roles in ensuring the successful green synthesis of nanoparticles with desired characteristics. Proper optimization of these parameters is critical for achieving reproducible and scalable nanoparticle production.

Applications of Green-Synthesized Nanoparticles

Green-synthesized nanoparticles have found extensive applications in medicine due to their biocompatibility and unique physicochemical properties [45]. One major application is in drug delivery, where nanoparticles serve as carriers for drug molecules. This enhances the stability, bioavailability, and targeted delivery of drugs, particularly in cancer treatment. For example, gold nanoparticles synthesized using plant extracts have shown potential in delivering anticancer drugs [46]. Additionally, silver nanoparticles are widely used as antimicrobial agents due to their ability to inhibit the growth of various bacteria and fungi. These nanoparticles are incorporated into wound dressings, coatings for medical devices, and antibacterial textiles to prevent infections [47]. Another important medical application involves magnetic nanoparticles like iron oxide, which are utilized as contrast agents in magnetic resonance imaging (MRI), improving the clarity and accuracy of diagnostic images [48].

In environmental remediation, green-synthesized nanoparticles play a crucial role due to their capability to interact with pollutants at the molecular level [49]. One key application is in water treatment, where nanoparticles, particularly silver nanoparticles, are used to remove heavy metals, organic pollutants, and pathogens from water. These nanoparticles have been shown to effectively purify water by eliminating bacteria and viruses [50]. Similarly, nanoparticles are employed in soil remediation to degrade organic pollutants or immobilize heavy metals, reducing their bioavailability and environmental impact [51]. This application helps in mitigating the risks associated with contaminated soils, improving environmental sustainability.

In the field of electronics, green-synthesized nanoparticles are utilized to enhance the performance of advanced devices and sensors [52]. One significant application is in sensors, where nanoparticles improve sensitivity and selectivity. Gold and silver nanoparticles are commonly used in biosensors for the detection of gases, chemicals, and biological molecules, making them valuable in medical diagnostics and environmental monitoring [53]. Additionally, nanoparticles are employed in conductive inks, which are crucial for printed electronics. These inks enable the development of flexible and wearable electronic devices, thereby expanding the possibilities for next-generation electronics [54].

The food industry also benefits from the application of green-synthesized nanoparticles. Food packaging materials enhanced with nanoparticles exhibit improved barrier properties, preventing the spoilage of food by blocking moisture, gases, and microbial contamination [55]. This contributes to better food quality and extended shelf life. Furthermore, antimicrobial nanoparticles, particularly silver nanoparticles, are incorporated into food preservation systems to inhibit microbial growth, ensuring food safety and reducing waste [56]. These applications demonstrate the potential of green-synthesized nanoparticles in enhancing the efficiency and sustainability of various industries.

Challenges and Future Prospects

The green synthesis of nanoparticles presents a sustainable and eco-friendly alternative to traditional chemical methods. However, challenges such as scalability, reproducibility, characterization, and toxicity continue to hinder its full potential. Addressing these hurdles is crucial for promoting the development and adoption of greener nanotechnology solutions.

One major challenge is scalability, where the difficulty lies in replicating laboratory-scale synthesis on an industrial scale while maintaining consistency in nanoparticle size, shape, and properties. Laboratory synthesis typically involves precise reaction conditions that are challenging to duplicate at larger scales [57]. Optimizing critical parameters like temperature, pH, and extract concentration is essential for large-scale production. Advanced bioreactor designs with automated control systems can help maintain process consistency during scale-up [60]. Additionally, continuous production methods offer greater efficiency and control compared to batch processing [58].

Another significant challenge is reproducibility, as variations in biological sources (e.g., plant species or microbial strains) and environmental factors affect nanoparticle synthesis [59]. Genetic variations and fluctuations in light, temperature, and humidity can cause inconsistencies in nanoparticle properties. Using clonal plant material or standardized microbial cultures can mitigate this issue. Automated systems for precise reaction control and monitoring can further improve reproducibility by minimizing human error [60].

Comprehensive characterization of nanoparticles is necessary to understand their properties and ensure they meet specific application requirements. Techniques such as transmission electron microscopy (TEM), dynamic light scattering (DLS), and X-ray diffraction (XRD) provide detailed insights into size, morphology, and surface chemistry [61], [10]. Standardized protocols and high-throughput screening technologies are crucial to ensure consistency and facilitate the rapid analysis of nanoparticles [62].

Despite the general perception that green-synthesized nanoparticles are safer, toxicity remains a concern. Thorough in vitro and in vivo studies are required to evaluate potential impacts on human health and the environment, including parameters such as cytotoxicity and genotoxicity [63]. For medical applications, ensuring biocompatibility involves extensive testing to assess nanoparticle interactions with biological systems [64]. Regulatory frameworks and safety guidelines will play a crucial role in ensuring responsible use across industries.

Looking forward, the future of green synthesis is promising. Integration with nanobiotechnology can foster innovations in drug delivery, diagnostics, and tissue engineering. Biocompatible nanoparticles can improve drug targeting and reduce side effects [65]. In sustainable agriculture, green-synthesized nanoparticles can contribute to environmentally friendly farming by enabling the development of nano-fertilizers, nano-pesticides, and soil-monitoring sensors [66].

Green-synthesized nanoparticles also hold potential for environmental remediation. They can address global water quality issues by removing contaminants like heavy metals, organic pollutants, and pathogens [50], [67]. These nanoparticles can also mitigate air and soil pollution, reducing the ecological footprint of industrial and agricultural activities [68].

In advanced manufacturing, green-synthesized nanoparticles can enhance the properties of materials used in additive manufacturing (3D printing), enabling the creation of customized, high-performance components. Additionally, stimuli-responsive smart materials incorporating nanoparticles have potential applications in healthcare, electronics, and textiles [69].

Collaborative research and development will be vital to overcoming these challenges. Interdisciplinary collaboration among chemists, biologists, engineers, and material scientists can drive the development of novel synthesis methods and applications. Public-private partnerships can accelerate commercialization efforts, ensuring the practical implementation of green nanotechnology innovations [70].

Conclusion

The green synthesis of nanoparticles offers a sustainable and eco-friendly alternative to conventional methods, leveraging biological entities such as plants, bacteria, fungi, and algae to reduce metal ions. This approach minimizes the use of toxic chemicals and energy-intensive processes, making it a promising avenue for environmentally conscious nanotechnology. Green-synthesized nanoparticles have shown immense potential across diverse sectors, including medicine, environmental remediation, electronics, and the food industry. Applications such as targeted drug delivery, antimicrobial agents, water purification, and food packaging exemplify the versatility of this method. However, several challenges must be addressed to unlock the full potential of green synthesis. Issues such as scalability, where maintaining consistency in nanoparticle properties during large-scale production is difficult, need innovative solutions like process optimization and automation. Reproducibility remains a concern due to variability in biological sources and environmental conditions. Developing standardized protocols and utilizing genetically uniform biological materials can mitigate this challenge. Accurate characterization of nanoparticles through advanced techniques like TEM, SEM, and DLS is also essential for ensuring their functional integrity. Additionally, thorough toxicity studies are crucial to ensure the biocompatibility and safety of nanoparticles, particularly in medical and environmental applications.

With ongoing research and technological advancements, green synthesis holds great promise for the development of safer, more efficient, and sustainable nanotechnology solutions. Collaborative efforts among researchers, industries, and regulatory bodies will be key to overcoming these challenges and driving the commercialization of green nanomaterials for various applications.

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