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Sustainable Nanotechnology: Advances in Green Synthesis and Applications of Nanoparticles

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Abstract

Green-synthesized nanoparticles have emerged as a viable alternative to traditionally synthesized nanoparticles, providing environmentally sustainable, biocompatible, and economical solutions across multiple sectors. This paper thoroughly examines current breakthroughs in the production of green nanoparticles, highlighting its medicinal, pharmacological, environmental, and agricultural uses. The shift from chemical and physical nanoparticle manufacturing to biological approaches including plants, microbes, and algae has reduced hazardous byproducts and enhanced stability and functional adaptability. Green-synthesized metal and metal oxide nanoparticles, including silver, gold, copper, titanium dioxide, and zinc oxide, have remarkable antibacterial, anticancer, and pollutant degradation properties. These nanoparticles are utilized in medicine delivery, photothermal therapy, wastewater treatment, and agricultural enhancement, establishing them as revolutionary materials for sustainable development. Notwithstanding their benefits, issues concerning synthesis scalability, batch-to-batch repeatability, and regulatory compliance continue to pose considerable obstacles to commercialization. Advanced characterisation approaches, computational modelling, and artificial intelligence-driven optimizations are being amalgamated to enhance nanoparticle synthesis processes, augment functionalization tactics, and guarantee safety evaluations. Prospects encompass hybrid green synthesis methods, genetically modified biosynthetic pathways, and biodegradable nanomaterials to improve efficiency and sustainability. This analysis emphasizes the pivotal importance of green nanotechnology in tackling urgent global issues in healthcare, environmental remediation, and energy conservation. By promoting interdisciplinary cooperation and standardizing synthesis techniques, green-synthesized nanoparticles can transform various industries while ensuring environmental sustainability and technical advancement. Ongoing research and innovation in this domain will be crucial for attaining widespread acceptance and commercial feasibility of green nanotechnology-based solutions.

Keywords: Green synthesis, nanoparticles, biomedical applications, environmental remediation, sustainable nanotechnology

1. Introduction

Nanotechnology, its distinctive physicochemical features, has significantly influenced various domains like medical, pharmacology, agriculture, and environmental remediation. A primary catalyst for these improvements is the production of nanoparticles (NPs) exhibiting size-dependent effects that markedly distinguish them from their bulk counterparts (Guilger-Casagrande et al., 2017; Fatima et al., 2015). Historically, physical and chemical synthesis methods necessitated toxic substances and energy-intensive processes, prompting concerns over environmental safety and economic viability. Conversely, green or biological synthesis utilizing plant extracts, microorganisms, fungi, algae, and biopolymers has arisen as a sustainable alternative that reduces ecological footprints while improving the inherent biocompatibility and stability of the resultant nanoparticles (Jeevanandam et al., 2022; Thacker et al., 2019). These approaches utilize the reducing, capping, and stabilizing properties of naturally occurring biomolecules, therefore limiting harmful by-products and conforming to global sustainability objectives (Kuppusamy et al., 2016).

The green production of nanoparticles in biomedicine and pharmaceuticals has enabled the creation of multifunctional drugs exhibiting significant antibacterial, antiviral, anticancer, antioxidant, and anti-inflammatory properties (Fatima et al., 2015; Hamrayev et al., 2021). Biologically produced silver and gold nanoparticles demonstrate exceptional cytocompatibility and inherent bioactivities, which have been utilized in targeted medication delivery and theranostic applications (Fatima et al., 2015; Wu et al., 2015). Recent studies indicate that nanoparticles synthesized through bio-mediated methods exhibit improved stability and reproducibility due to natural capping by proteins and other biomolecules, thereby addressing the limitations of synthetic alternatives (Hamrayev et al., 2021; Jeevanandam et al., 2022). These nanoparticles are progressively included into nanoencapsulation methods to enhance the controlled release and bioavailability of medicines, thus tackling significant issues in pharmacokinetics and pharmacodynamics (Hamrayev et al., 2021; Wu et al., 2015).

Sustainable nanoparticle production has also benefited environmental cleanup and agricultural uses. Green-synthesized nanoparticles demonstrate elevated surface reactivity and improved adsorption capabilities, making them highly efficient in the catalytic degradation of contaminants, heavy metals, and organic dyes from wastewater (Thacker et al., 2019; Sardul et al., 2017). In agriculture, these environmentally benign nanoparticles function as elicitors and stimulators for plant growth, nutrient absorption, and stress resilience, ultimately enhancing crop output and quality (Kuppusamy et al., 2016; Sardul et al., 2017). The use of plant extracts and biopolymers diminishes dependence on conventional agrochemicals and enables the production of nanoparticles that serve as diagnostic and therapeutic agents (Kuppusamy et al., 2016; Sardul et al., 2017).

Furthermore, multidisciplinary methods currently combine omics technology with machine learning to elucidate and enhance the biochemical pathways responsible for nanoparticle formation. This synergy facilitates the predictive modelling of nanoparticle properties by linking synthesis circumstances with particle size, shape, and functional characteristics (Bannigidad et al., 2023; Jeevanandam et al., 2022). This integration has expedited the identification of effective synthesis techniques and enhanced the advancement of scalable, uniform production systems. Nonetheless, obstacles persist, such as regulatory ambiguities, cost scalability issues, and insufficient toxicity profiles, requiring comprehensive lifecycle assessments and extensive long-term effect research (Roy et al., 2022; Adil et al., 2015).

The transition to green production of nanoparticles represents a notable progression in sustainable engineering and materials research. Researchers are utilizing sustainable biological approaches to tackle environmental and economic issues while broadening the applications of nanoparticles in medicinal, pharmaceutical, agricultural, and environmental remediation sectors. Ongoing research that incorporates cutting-edge interdisciplinary methodologies is expected to enhance synthesis protocols, thereby realizing the complete potential of these revolutionary nanomaterials in tackling current global issues (Guilger-Casagrande et al., 2017; Fatima et al., 2015; Jeevanandam et al., 2022; Hamrayev et al., 2021; Thacker et al., 2019; Adil et al., 2015).

2. Green Synthesis Methods and Mechanisms

The eco-friendly synthesis of nanoparticles has attracted significant interest as a safer alternative to conventional chemical and physical methods that frequently utilize toxic reagents, require substantial energy, and produce environmentally harmful byproducts (Ahmed & Mustafa, 2019; Shydlovska & Kharchenko, 2022). Traditional methods need harsh reaction conditions and produce toxic residues, hence restricting their use in biomedical and environmental applications. In contrast, green synthesis utilizes biological entities—such as plants, fungus, bacteria, algae, and biopolymers to facilitate nanoparticle creation under mild conditions, resulting in diminished toxicity and reduced energy consumption, thereby closely fitting with sustainable development objectives (Ahmad, 2017).

Plant-mediated synthesis is a prominent green methodology, chiefly due to the abundance of bioactive phytochemicals in plants, such as polyphenols, flavonoids, tannins, alkaloids, proteins, and enzymes. These chemicals function as reducing agents to convert metal ions to their zero-valent or oxide states and as stabilizing agents to inhibit agglomeration, thus regulating the size and morphology of the nanoparticles (Basavegowda et al., 2013; Dauthal & Mukhopadhyay, 2016). Fruit extracts from Ananas comosus have effectively synthesized gold nanoparticles, exhibiting quick reduction kinetics and significant biological activity (Basavegowda et al., 2013). Lemon leaf extracts have been shown to markedly reduce reaction times, demonstrating the efficacy of phytochemical-mediated mechanisms (Vankar & Shukla, 2011). The inherent capacity of plant extracts to both decrease and stabilize nanoparticles obviates the necessity for supplementary synthetic stabilizers, thus improving biocompatibility for prospective biomedical uses, including anticancer therapy and antibacterial treatments (Santhanam et al., 2019).

Besides plant extracts, microbial-mediated synthesis utilizes bacteria, fungus, and yeast that excrete enzymes and other metabolites to catalyse the reduction of metal ions into nanoparticles (Shydlovska & Kharchenko, 2022). Fungi are beneficial as their extracellular secretions promote the creation and subsequent retrieval of nanoparticles with minimal purifying processes. Algae-mediated pathways provide advantages owing to their metal bioaccumulation capabilities and their functionality in both extracellular and intracellular environments. Simultaneously, the synthesis employing natural biopolymers such chitosan and cellulose improves nanoparticle stability by minimizing aggregation and offering functional groups for additional modifications (Shydlovska & Kharchenko, 2022).

The primary mechanism of green nanoparticle production consists of three stages: bio reduction, nucleation, and stability. In the bio reduction phase, biomolecules transfer electrons to metal ions, commencing their transformation into the metallic state. Nucleation ensues, wherein the reduced atoms aggregate to form tiny clusters that develop into nanoparticles; the nucleation rate is a pivotal determinant of the final size and dispersity of the product (Ahmed & Mustafa, 2019). Stabilization is ultimately attained as diverse biomolecules, such as polysaccharides and organic acids, adhere to the surfaces of nanoparticles; this mechanism inhibits further aggregation and determines subsequent physicochemical properties essential for applications in catalysis, environmental remediation, and medicine (Ahmad, 2017; Çelebioğlu et al., 2021).

Notwithstanding the significant benefits of green synthesis namely diminished environmental impact, economic efficiency, and scalability challenges persist in regulating repeatability and attaining homogeneity in particle size and morphology. Fluctuations in the composition and concentration of biological extracts can result in inconsistencies between batches, thus requiring the optimization of reaction parameters including pH, temperature, precursor and extract concentrations, and reaction duration (Ahmed & Mustafa, 2019; Shydlovska & Kharchenko, 2022). It is imperative to tackle these issues by standardization and the amalgamation of hybrid approaches that merge green synthesis with sophisticated nanofabrication techniques for the extensive industrial and biological utilization of nanoparticles (Ahmad, 2017; Çelebioğlu et al., 2021).

The green synthesis of nanoparticles signifies a transition from perilous chemical techniques to sustainable, environmentally friendly approaches that efficiently employ natural resources. Researchers have developed economical and biocompatible methods for nanoparticle fabrication by utilizing the reducing power and stabilizing properties of bioactive compounds derived from plants, microbes, algae, and biopolymers (Basavegowda et al., 2013; Vankar & Shukla, 2011; Lee et al., 2013). Ongoing endeavours to refine these approaches and tackle scalability issues are anticipated to maximize the potential of green synthesis in fields such as nanomedicine and environmental remediation.

3. Types of Green-Synthesized Nanoparticles and Their Properties

Green-synthesized nanoparticles have arisen as a sustainable, environmentally friendly alternative to traditional synthesis processes, providing a wide array of nanomaterials that can be categorized based on their composition. The synthesis is generally conducted under mild circumstances utilizing plant extracts, microbial cultures, or algal agents as reducing and stabilizing agents, thereby ensuring minimal toxicity and improved biocompatibility (Soltys et al., 2021; Henríquez et al., 2020). This eco-friendly approach not only reduces toxic consequences but also offers a natural source of functional biomolecules suitable for surface modification and specific applications.

Metal nanoparticles, including those made of gold, silver, copper, and platinum, constitute one of the most thoroughly researched categories. Gold nanoparticles (AuNPs) produced by green chemistry methods possess distinctive optical and catalytic characteristics, rendering them suitable for drug administration, imaging, and photothermal therapy (Ghosh et al., 2020; Geetha et al., 2013). Their synthesis utilizing extracts from plants such as Camellia sinensis offers a reliable method to produce nanoparticles that demonstrate good stability and low cytotoxicity (Geetha et al., 2013). Likewise, silver nanoparticles (AgNPs) synthesized from extracts of Azadirachta indica and Ocimum sanctum exhibit a robust antibacterial spectrum and notable anticancer efficacy (Mie et al., 2013; Verma & Mehata, 2016). Copper nanoparticles (CuNPs) produced from tea leaf extracts exhibit significant antibacterial and catalytic capabilities; however, their stability may be compromised by oxidation (Lee et al., 2013; Iorhuna et al., 2022). Platinum nanoparticles (PtNPs), synthesized by environmentally friendly methods, have exceptional catalytic efficiency and have been investigated for cancer therapy and biosensing due to their bioinert properties (Bhaumik et al., 2015).

Metal oxide nanoparticles, such as titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_3O_4), constitute a significant category. Green-synthesized TiO_2 nanoparticles demonstrate superior photocatalytic capabilities, facilitating their application in environmental remediation procedures as wastewater treatment and air purification, frequently utilizing plant polyphenols as reducing agents (Miu et al., 2024). Zinc oxide nanoparticles produced from Citrus sinensis exhibit regulated size and morphology, which emphasize their antibacterial properties and appropriateness for use in wound dressings and sunscreens (Khanal et al., 2020). Moreover, iron oxide nanoparticles, often synthesized from Camellia sinensis extracts, demonstrate superparamagnetic properties that are beneficial for targeted drug delivery, magnetic resonance imaging (MRI), and hyperthermia therapies (Franco et al., 2021).

Bimetallic nanoparticles created by green technologies, alongside mono-metal and oxide nanoparticles, have garnered interest for their synergistic features. Combining two distinct metal constituents (e.g., Ag-Au, Cu-Ag, or Au-Pt) often results in nanomaterials that demonstrate superior catalytic, antibacterial, and optical properties relative to their monometallic equivalents, thereby broadening their applicability in biosensing, catalysis, and nanomedicine (Soltys et al., 2021).

Organic nanoparticles originating from natural biopolymers, including chitosan, cellulose, and plant gums, have significant benefits for biocompatibility and biodegradability. Chitosan-based nanoparticles have been thoroughly investigated for drug delivery applications owing to their mucoadhesive characteristics and adjustable release profiles (Pooja et al., 2015). Cellulose nanoparticles derived from plant fibers are utilized as sustainable materials for biomedical implants and packaging due to their superior mechanical qualities and intrinsic biodegradability (Soltys et al., 2021). Natural gum-based nanoparticles promote stabilization during synthesis and improve the environmentally friendly aspects of the production process, hence expanding their applicability in medicinal and industrial product formulations (Soltys et al., 2021).

The physicochemical characteristics of green-synthesized nanoparticles, including particle size, morphology, surface charge, and functionalization capacity, are significantly affected by synthesis parameters such as reaction pH, precursor concentration, temperature, and incubation duration (Soltys et al., 2021; Gao et al., 2022). A mildly alkaline pH has been shown to promote the creation of smaller, more stable AgNPs, while variations in temperature influence the nucleation and growth kinetics, hence regulating the final shape of the nanoparticles (Gao et al., 2022). Surface functionalization improves the stability and dispersibility of nanoparticles while offering active sites for conjugation with therapeutic agents, proteins, or targeting ligands, which is essential for biomedical applications such as targeted drug delivery and biosensor development (Bhaumik et al., 2015; Pooja et al., 2015).

The extensive applications of green-synthesized nanoparticles encompass biological, environmental, and industrial domains. In medicine, AuNPs and AgNPs are extensively utilized for antimicrobial coatings, cancer treatment, diagnostic imaging, and drug delivery systems, leveraging their distinctive optical, electrical, and catalytic characteristics (Geetha et al., 2013; Mie et al., 2013; Verma & Mehata, 2016). Metal oxides like ZnO and TiO_2 are pivotal in photocatalysis and pollutant degradation, highlighting their effectiveness in environmental remediation and self-cleaning coatings (Miu et al., 2024; Khanal et al., 2020). Moreover, the synergistic interactions inside bimetallic nanoparticles augment their catalytic efficacy, hence facilitating progress in chemical synthesis and biosensing (Soltys et al., 2021). Notwithstanding these advantageous characteristics, obstacles including reproducibility, scalability, and thorough toxicity evaluations persist as significant impediments to clinical translation and extensive commercial implementation (Soltys et al., 2021; Henríquez et al., 2020).

The green synthesis of nanoparticles offers a versatile, sustainable, and environmentally friendly method for producing a variety of nanomaterials with customized physicochemical characteristics. These nanoparticles, encompassing metal, metal oxide, bimetallic, and organic varieties, have exhibited potential in healthcare, environmental remediation, and industrial catalysis, highlighting their crucial position in the advancement of nanotechnology with diminished environmental impact. Future research must concentrate on refining synthesis processes, standardizing manufacturing techniques, and performing comprehensive safety assessments to fully exploit the potential of green-synthesized nanoparticles for various applications.

Table 1: Green-Synthesized Nanoparticles and Their Properties

Type	Properties	**Citation**
Gold Nanoparticles	Used in drug delivery, imaging, and photothermal therapy	(Ghosh et al., 2020; Geetha et al., 2013)
Silver Nanoparticles	Exhibit antibacterial and anticancer properties	(Mie et al., 2013; Verma & Mehata, 2016)
Copper Nanoparticles	Antibacterial and catalytic capabilities, but susceptible to oxidation	(Lee et al., 2013; Iorhuna et al., 2022)
Platinum Nanoparticles	High catalytic efficiency; used in cancer therapy and biosensing	(Bhaumik et al., 2015)
Titanium Dioxide Nanoparticles	Photocatalytic applications in environmental remediation	(Miu et al., 2024)
Zinc Oxide Nanoparticles	Antibacterial properties; used in wound dressings and sunscreens	(Khanal et al., 2020)
Iron Oxide Nanoparticles	Superparamagnetic properties for drug delivery and MRI	(Franco et al., 2021)
Bimetallic Nanoparticles	Enhanced catalytic, antibacterial, and optical properties	(Soltys et al., 2021)
Chitosan-based Nanoparticles	Mucoadhesive properties for drug delivery	(Pooja et al., 2015)
Cellulose-based Nanoparticles	Used in biomedical implants and packaging	(Soltys et al., 2021)

Natural Gum-based Nanoparticles	Enhance stability and eco-friendliness in synthesis	(Soltys et al., 2021)

4. Multifunctional Applications of Green-Synthesized Nanoparticles

Green-synthesized nanoparticles have garnered considerable interest as multifunctional materials owing to their environmentally friendly synthesis, intrinsic biocompatibility, and cost efficiency, especially when juxtaposed with traditional physical or chemical methods (Abbasi et al., 2019; Fierăscu et al., 2017). The utilization of biological reducing agents, including plant extracts rich in various phytochemicals, reduces the production of harmful by-products and imparts advantageous surface properties to nanoparticles, thereby augmenting their reactivity and applicability (Abbasi et al., 2019; Fierăscu et al., 2017).

In biomedical sciences, green-synthesized nanoparticles are distinguished for their antibacterial, antiviral, anticancer, and anti-inflammatory characteristics. Silver nanoparticles synthesized via Phyto-mediated methods utilizing extracts from Azadirachta indica, Moringa oleifera, or Aloe vera demonstrate significant surface reactivity, which promotes the disruption of bacterial cell membranes and the inhibition of microbial growth (Fierăscu et al., 2017). These nanoparticles have been included into wound dressings, medical device coatings, and antibacterial textiles to address hospital-acquired infections and antibiotic-resistant organisms (Fierăscu et al., 2017). Moreover, gold nanoparticles synthesized using analogous green methods have been utilized in cancer therapy, specifically through photothermal therapies that convert light to heat, causing necrosis in cancer cells while minimizing harm to healthy tissues (Kaur et al., 2023).

From a pharmacological standpoint, green-synthesized nanoparticles function as sophisticated drug delivery systems that enhance the solubility, stability, and bioavailability of medicinal agents. Nanoparticulate carriers, typically sourced from biogenic gold and silver, can be functionalized with biomolecules like proteins, peptides, or antibodies for receptor-mediated targeting and regulated drug release. This modification improves treatment specificity and reduces systemic toxicity (Anjum et al., 2021). Furthermore, metal oxide nanoparticles (e.g., TiO_2 and ZnO) produced using eco-friendly processes utilize natural stabilizing agents such as polysaccharides and flavonoids, which improve their efficacy in dermatological applications (Buarki et al., 2022; Anjum et al., 2021).

Environmental remediation is a significant application in which, green-synthesized nanoparticles demonstrate superior efficacy. Due to their elevated surface area-to-volume ratios and intrinsic catalytic properties, nanoparticles like silver, iron oxide, and titanium dioxide efficiently adsorb and degrade heavy metals, organic dyes, and other contaminants in polluted water sources (Abbasi et al., 2019; Fierăscu et al., 2017). Their photocatalytic characteristics, enhanced by bio functional groups from plant extracts, assist in the degradation of persistent organic pollutants, providing sustainable options for industrial wastewater treatment (Abbasi et al., 2019).

Agricultural applications have also gained advantages from nanoparticles produced via eco-friendly processes. Their application as nano-pesticides and biofertilizers demonstrates potential in enhancing plant growth, optimizing nutrient absorption, and increasing crop resilience to diseases. Zinc oxide and copper oxide nanoparticles produced using environmentally friendly methods have shown improvements in photosynthetic efficiency and stress resilience in plants (Ndou et al., 2023). Likewise, silver nanoparticles demonstrate antifungal properties, enhancing plant growth and boosting agricultural productivity (Ndou et al., 2023).

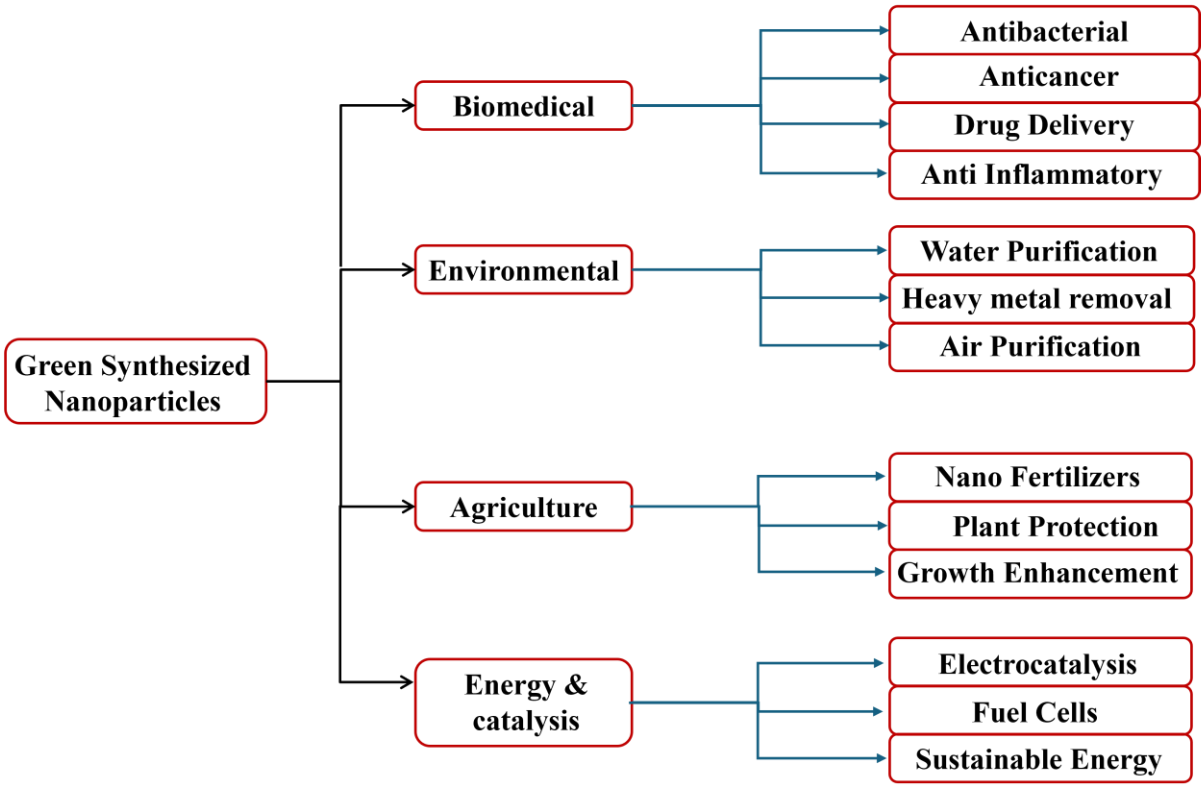

Fig 1. Applications of Green-Synthesized Nanoparticles.

Bimetallic nanoparticles synthesized by environmentally friendly methods demonstrate beneficial features for catalytic processes and electrocatalysis in energy storage and catalysis. Alloys like silver-gold (Ag-Au) enhance electron transfer kinetics and fuel cell efficacy while facilitating efficient hydrogen evolution (AbdelHamid et al., 2013). These attributes are crucial for enhancing energy conversion processes and creating next-generation catalysts designed for sustainable energy applications (AbdelHamid et al., 2013).

Despite various promising applications, issues persist concerning the scalability, repeatability, and standardization of green synthesis procedures. The variability in biological extracts affects the size, shape, and stability of nanoparticles, requiring enhanced interdisciplinary collaboration to establish automated, reliable production methods while ensuring prolonged biocompatibility and environmental safety (Abbasi et al., 2019; Anjum et al., 2021). Future advancements are expected to emerge from the integration of green nanotechnology with nascent disciplines like nanobiotechnology and synthetic biology, facilitating the exact design of multifunctional nanoparticles customized for specific purposes.

Table 2: Applications of Green-Synthesized Nanoparticles

Application	Description	Citation
Biomedical Applications	Silver nanoparticles exhibit antibacterial, antiviral, anticancer, and anti-inflammatory properties.	(Fierafscu et al., 2017)
Wound Healing	Silver nanoparticles used in wound dressings and antibacterial textiles.	(Fierafscu et al., 2017)
Cancer Therapy	Gold nanoparticles enable photothermal therapy for cancer treatment.	(Kaur et al., 2023)
Drug Delivery	Nanoparticles enhance solubility, stability, and bioavailability of drugs.	(Anjum et al., 2021)
Environmental Remediation	Silver, iron oxide, and titanium dioxide nanoparticles degrade pollutants.	(Abbasi et al., 2019; Fierafscu et al., 2017)
Wastewater Treatment	Photocatalytic properties help in the removal of persistent organic pollutants.	(Abbasi et al., 2019)
Agriculture	Zinc oxide and copper oxide nanoparticles improve plant growth and stress resilience.	(Ndou et al., 2023)
Antifungal Properties	Silver nanoparticles enhance plant health and increase agricultural productivity.	(Ndou et al., 2023)
Energy Storage and Catalysis	Silver-gold nanoparticles improve fuel cell efficiency.	(Abdelhamid et al., 2013)
Hydrogen Evolution	Bimetallic nanoparticles enhance energy conversion processes.	(Abdelhamid et al., 2013)

5. Advanced Techniques in Nanoparticle Research

Recent improvements in the production and implementation of green-synthesized nanoparticles have been driven by progress in multi-omics analysis, artificial intelligence (AI), machine learning (ML), high-resolution characterisation, and computational modelling. These technologies provide exact regulation of nanoparticle physicochemical characteristics and improve reproducibility, scalability, and specific functionality.

Multi-omics methodologies, encompassing genomes, transcriptomics, proteomics, and metabolomics, elucidate the biosynthetic pathways governing nanoparticle synthesis in plant and microbial systems. Genomic investigations uncover essential genes and enzymes involved in metal ion reduction and stabilization, whereas proteomics clarifies the functions of reductases and capping proteins that regulate nanoparticle form and stability (Jain et al., 2024). Metabolomics delineates secondary metabolites such as flavonoids, polyphenols, and alkaloids that function as reducing and capping agents, thereby enhancing the biological extracts employed in nanoparticle formation (Jain et al., 2024). This integrated omics strategy elucidates the molecular pathways involved and facilitates bioengineering methods to augment nanoparticle production.

The incorporation of AI and ML into nanoparticle synthesis enhances research potential by facilitating predictive modelling of nanoparticle characteristics. AI algorithms use extensive information from experimental and omics research to determine ideal synthesis settings, precisely forecasting factors such as size, shape, surface charge, and stability (Shoaib et al., 2024). Moreover, machine learning algorithms enable high-throughput screening of diverse biological extracts, thereby substantially decreasing the experimental costs and time necessary for optimizing nanoparticle production (Shoaib et al., 2024). These computational methods are essential for the design of intelligent nanocarriers for drug administration, as simulations of nanoparticle–drug interactions and controlled release mechanisms improve therapeutic efficacy.

High-resolution characterisation techniques enhance these advanced synthesis and design methods by confirming the structural and functional properties of green-synthesized nanoparticles. Techniques including transmission electron microscopy (TEM), scanning electron microscopy (SEM), atomic force microscopy (AFM), and dynamic light scattering (DLS) yield comprehensive morphological and size distribution data, whereas spectroscopic methods such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy elucidate crystallinity and surface functionalization (Sondezi et al., 2024). These sophisticated imaging and spectroscopic instruments guarantee that the synthesized nanoparticles demonstrate the requisite homogeneity, monodispersity, and biocompatibility for use in biomedicine, catalysis, and environmental remediation.

Furthermore, computer modelling and molecular dynamics simulations are essential tools for clarifying the mechanisms of nanoparticle production and interaction. These simulations provide insights into nanoparticle stability, aggregation kinetics, and biomolecular interactions, connecting theoretical predictions with empirical data to optimize synthesis parameters (Ravi et al., 2022). Innovative hybrid synthesis methods that include plant-mediated, microbial-assisted, and enzymatic techniques present significant opportunities for the large-scale fabrication of nanoparticles with enhanced bioactivity and environmental compatibility (Jain et al., 2021). The integration of these methodologies with sustainable bio fabrication techniques enhances the practical utilization of green nanoparticles in targeted drug delivery and sustainable packaging materials.

The integration of multi-omics analysis, AI-driven predictive modelling, high-resolution characterisation, and computer simulation is revolutionizing green nanoparticle research. This interdisciplinary integration enhances comprehension of nanoparticle biogenesis and facilitates the design of multifunctional, intelligent nanomaterials customized for biomedical and industrial uses. As research in this field advances, the incorporation of these sophisticated techniques is anticipated to expedite the evolution of sustainable nanotechnologies that tackle global issues in healthcare and environmental preservation (Jain et al., 2024; Jain et al., 2021; Sondezi et al., 2024; Ravi et al., 2022).

6. Challenges and Future Prospects

The advancement in green synthesis of nanoparticles is accompanied by various hurdles, including scalability, repeatability, toxicity uncertainty, and economic viability. Unlike traditional chemical methods that provide exact reaction control and consistent nanoparticle properties, biologically mediated processes often display significant variability owing to the heterogeneous composition of reducing and stabilizing agents found in plant, microbial, and algal extracts. Variability in phytochemical content can result in variations in particle size, shape, and stability, as demonstrated in research indicating discrepancies among plant species and seasonal changes (Logaranjan et al., 2016; Álvarez-Chimal & Arenas-Alatorre, 2023). This variability hinders the standardization process required for industrial applications and regulatory approval.

The absence of scalability and repeatability in green synthesis is further intensified by the intrinsic complexity of reaction dynamics. Green synthetic approaches typically exhibit reduced reaction speeds relative to conventional chemical procedures, facing difficulties due to inadequately regulated nucleation and growth processes. Continuous flow procedures have been examined to address heat gradient and mixing challenges; yet these strategies continue to encounter constraints in attaining uniform product quality at increased volumes, as articulated by Hallot et al. Hallot et al. (2021) and corroborated by Vreeland et al. (2015). Furthermore, repeatability issues arise from fluctuating biological inputs and the inherent kinetic complexity of nanoparticle production processes, rendering scale-up to pilot or industrial levels very difficult (Colby et al., 2021).

A notable research gap persists in the thorough comprehension of the environmental and biological effects of green-synthesized nanoparticles. While natural capping agents from biological extracts often provide biocompatibility, the interactions between nanoparticles and biological systems are intricate. The dimensions, shape, and surface charge of nanoparticles might influence their biodistribution, cellular absorption, and long-term bioaccumulation, potentially resulting in cytotoxicity and genotoxicity issues (Thomas et al., 2022). Furthermore, the degradation mechanisms and environmental longevity of these nanoparticles are inadequately defined (Mustapha et al., 2022). This necessitates the creation of standardized toxicity testing techniques and environmental risk assessment models to guarantee safe implementation in biomedical, agricultural, and environmental contexts.

Economic and logistical obstacles impede the transfer from laboratory-scale trials to commercial production. The upkeep of biological cultures, extraction processes, and ensuing purification stages may result in elevated manufacturing expenses relative to chemical synthesis methods. Reports indicate that although plant-mediated synthesis may be cost-effective on a local scale, challenges such as impurity removal and nanoparticle yield optimization render large-scale application prohibitively expensive without additional process innovations (Kumbharkhane, 2024). The necessity for regulated fermentation in microbiological methods increases the total operational costs (Jain et al., 2024). Addressing these problems necessitates the incorporation of continuous flow synthesis and automation technologies, which are expected to improve uniformity and decrease manufacturing costs.

Future directions indicate that interdisciplinary advancements, especially through the amalgamation of synthetic biology, genetic engineering, and artificial intelligence (AI), present promising solutions to address existing difficulties. Progress in metabolic engineering and the creation of genetically engineered organisms can enhance the regulation of nanoparticle properties by accurately adjusting enzymatic pathways involved in bio reduction, thus improving yield and consistency (Singh et al., 2024). Simultaneously, machine learning techniques are utilized to optimize reaction parameters in real time, diminishing dependence on trial-and-error experimentation and expediting the identification of innovative synthesis methods that can further standardize nanoparticle production (Jain et al., 2024). These novel methodologies are anticipated to enable the conversion of green nanotechnology into therapeutically and industrially feasible goods.

Ultimately, regulatory and ethical factors are crucial in the widespread use of green-synthesized nanoparticles. The implementation of defined nanoparticle characterisation techniques, rigorous quality control measures, and comprehensive risk assessment frameworks is crucial for the safe integration of these materials into consumer markets. The regulatory issues are exacerbated by the variety of synthesis processes, necessitating extensive collaboration among academic researchers, industry stakeholders, and regulatory authorities to align guidelines and safeguard public safety (Gessner, 2021). Although substantial advancements have been achieved in green nanotechnology, it is essential to tackle these interrelated obstacles for its sustainable and extensive implementation in medical, environmental remediation, agriculture, and other fields.

7. Conclusion

The current transition to green synthesis methods in nanotechnology has initiated a revolution by substituting previous environmentally detrimental strategies with eco-friendly, cost-effective, and sustainable alternatives. In these methodologies, biological resources comprising plant extracts, microbes, and algae function as reducing and stabilizing agents to synthesize metal nanoparticles with enhanced biocompatibility and functional characteristics (Abu-Dief et al., 2020; Shukla et al., 2017). This change is based on green chemistry concepts that minimize the necessity for high-energy inputs and hazardous chemicals, therefore facilitating safer nanoparticle production and diminishing environmental concerns (Abu-Dief et al., 2020; Vijayaram et al., 2023). The distinctive physicochemical characteristics of nanoparticles produced by green technologies, including elevated surface area-to-volume ratios, adjustable optical and electrical properties, and straightforward functionalization, have facilitated various applications. These applications encompass biomedicine, where green nanoparticles serve as promising drug delivery systems, diagnostic tools, and therapeutic agents for cancer treatment (Kiani et al., 2022; Mbatha et al., 2023), as well as environmental remediation, agriculture, and energy storage sectors (Shukla et al., 2017; Vijayaram et al., 2023). Plant-mediated synthesis has been shown to produce nanoparticles with size and shape distributions like those generated by traditional methods, hence guaranteeing efficacy in catalytic and antibacterial functions (Shukla et al., 2017). Similarly, the inherent biocompatibility and environmental sustainability of these nanoparticles support their increasing utilization in high-value applications, including precision medicine and advanced agriculture techniques (Abu-Dief et al., 2020; Kulkarni et al., 2023).

Notwithstanding these developments, obstacles remain in the large-scale manufacture and uniform quality control of green-synthesized nanoparticles. Variations in the chemical composition of biological extracts might result in discrepancies in nanoparticle size, shape, and stability, hence challenging reproducibility and scalability (Tareq et al., 2022; Khandel & Shahi, 2018). Furthermore, the absence of established methodologies and thorough toxicity evaluations generates regulatory apprehensions about safety in both industrial manufacturing and consumer application (Tareq et al., 2022; Grasso et al., 2019). Resolving these difficulties necessitates the formulation of integrated protocols that amalgamate improved characterisation, predictive modelling, and high-throughput screening techniques. The future integration of interdisciplinary techniques, including artificial intelligence, synthetic biology, and microfluidic continuous processing, shows significant potential for enhancing nanoparticle manufacturing. Hybrid methodologies that systematically integrate plant, microbial, and enzymatic pathways are anticipated to significantly improve the stability and scalability of nanoparticle synthesis (Khandel & Shahi, 2018). These innovations not only enhance the functional precision and efficiency of nanoparticles for applications from catalytic processes to targeted cancer therapies but also herald a new era of sustainable industrial practices that prioritize environmental stewardship (Vijayaram et al., 2023; Hallot et al., 2025). Cooperative endeavours among chemists, engineers, biologists, and regulatory agencies will be essential in developing rigorous synthesis protocols and safety regulations, thus enabling green nanotechnology to achieve its transformative potential across various industries while tackling pressing global issues.

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