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Eco-Friendly Fabrication of Nanomaterials and Nanocomposites via Green Synthesis Strategies

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Abstract: *Concerns about the effects of conventional synthesis methods on the environment and human health have been highlighted by the growing demand for nanomaterials and nanocomposites in a variety of industries. High energy input, harmful reducing agents, and toxic solvents are frequently used in traditional physical and chemical fabrication processes, which have a substantial waste and environmental impact.*
As a result, green synthesis techniques have surfaced as sustainable substitutes that make use of energy-efficient procedures, environmentally safe solvents, and renewable biological resources. With a focus on plant-mediated, microbial, biopolymer-assisted, and green physical methods, this chapter provides a thorough overview of environmentally friendly production techniques for nanomaterials and nanocomposites.
A critical discussion is held on the mechanisms of nanoparticle formation, the creation of green nanocomposites, characterization methods, and significant applications in the industrial, biomedical, environmental, and energy sectors. Future prospects and present obstacles to the widespread application and commercialization of green nanotechnology are also emphasized.

Keywords: Green synthesis, nanomaterials, nanocomposites, sustainable nanotechnology, eco-friendly fabrication.

I. INTRODUCTION

Advanced materials with remarkable physicochemical properties, such as high surface area, tunable optical behavior, increased catalytic efficiency, and higher mechanical strength, have been made possible by the quick growth of nanoscience and nanotechnology. These special qualities have put nanoparticles at the forefront of advancements in food packaging, agriculture, energy storage, biomedical engineering, and environmental cleanup. However, traditional physical and chemical techniques for creating nanoparticles frequently depend on dangerous solvents, toxic reducing agents, and energy-intensive procedures, raising major issues for the environment and human health. As a result, there is increasing interest in creating ecologically friendly and sustainable methods for producing nanomaterials and nanocomposites.

Green synthesis is based on Anastas and Warner's green chemistry principles, which emphasize reducing dangerous chemicals, reducing waste, and improving energy efficiency in chemical processes [3]. applying these ideas to the production of nanomaterials has led to the development of environmentally friendly synthesis techniques that employ renewable biological resources as reducing and stabilizing agents. These techniques offer inexpensive, scalable, and biocompatible alternatives to traditional synthesis techniques in addition to eliminating dangerous materials [20, 33].

Plant-mediated synthesis has drawn a lot of interest among green methods because of its ease of use, accessibility to raw materials, and capacity to generate nanoparticles in mild environments. Flavonoids, phenolics, alkaloids, and terpenoids are examples of phytochemicals found in plant extracts that function as natural reducing and capping agents, allowing for the regulated creation of nanoparticles without the need for additional surfactants [2,31,38]. Numerous investigations have shown that plants can synthesize silver, gold, zinc oxide, titanium dioxide, and selenium nanoparticles with potential uses in agriculture, medicine, and environmental preservation [14,18,21,29]. The dependability of plant-mediated green synthesis is strengthened by recent reviews that emphasize the molecular knowledge of phytochemical-driven reduction and stabilization processes [36, 38].

Another environmentally friendly method is microorganism-assisted synthesis, in which bacteria, fungi, and algae use metabolic and enzymatic processes to transform metal ions into nanoparticles. The creation of intracellular or extracellular nanoparticles with regulated morphology and high stability is made possible by this biological detoxification process [11,16,23,30]. Because of their increased biocompatibility and antibacterial activity, noble metal nanoparticles produced by bacteria and fungi have demonstrated great promise in medicinal applications [11, 30]. Green fabrication techniques have been extended to agricultural applications through the employment of rhizobacteria that promote plant growth for the synthesis of nanoparticles [32].

Because of their biodegradability, lack of toxicity, and abundance of functional groups, biopolymers like chitosan, cellulose, starch, gelatin, and glycogen have become viable matrices for creating nanocomposites. Food packaging, wound healing, and drug delivery applications can benefit from the mechanical strengthening, increased antibacterial qualities, and improved thermal stability that biopolymer-based nanocomposites offer [8,17,24,34,39]. Excellent antibacterial and antioxidant properties have been demonstrated by green-fabricated chitosan/ZnO, cellulose/ZnO, and starch-based nanocomposites, demonstrating their multifunctional potential [24–28]. Notably, starch and glycogen nanocomposites doped with selenium nanoparticles and produced using environmentally friendly methods have shown therapeutic antibacterial and anti-inflammatory properties, underscoring their medicinal significance [1,28].

Because of their many functional characteristics, metal and metal oxide nanoparticles continue to be the most extensively studied class of green-synthesized nanomaterials. Silver nanoparticles have been widely used in water disinfection and medicinal coatings due to their potent antibacterial properties [18]. Gold nanoparticles are useful for imaging and cancer treatment due to their special optical and photothermal characteristics [13] Nanoparticles of zinc oxide and titanium dioxide exhibit photocatalytic activity for self-cleaning materials and environmental remediation [14,26]. Stable and crystalline structures are produced while lowering environmental risks by the green synthesis of these nanoparticles utilizing plant extracts or biopolymers [21,25,29].

Simultaneously, carbon-based nanomaterials made from biomass resources have drawn interest as environmentally friendly substitutes for traditional carbon nanostructures. Carbon nanotubes and graphene-like materials generated from biomass have demonstrated intriguing uses in catalytic processes, adsorption systems, and supercapacitors [6]. These developments highlight the fact that green synthesis encompasses high-performance functional nanomaterials in addition to metallic nanoparticles.

Mechanical strength, thermal stability, and biological activity can all be enhanced synergistically by nanocomposites that include nanoparticles into polymeric or inorganic matrices. Green nanoparticle synthesis and biodegradable polymer matrices are used in environmentally friendly nanocomposite manufacturing to create sustainable materials for biomedical implants, sensors, antimicrobial coatings, and environmental remediation [9,10,34,39]. Recent research on more environmentally friendly nano-biopolymers and nanoencapsulation systems emphasizes their potential for industrial translation as well as their decreased ecological impact [9,10].

To verify particle formation, stability, and functional performance, green-synthesized nanomaterials must be characterized. Size, crystallinity, surface chemistry, and morphology are frequently evaluated using methods such Fourier transform infrared spectroscopy, X-ray diffraction, electron microscopy, and UV-visible spectroscopy [4,12,15]. For commercial applications, accurate characterisation promotes scale-up viability and guarantees reproducibility.

Large-scale production, repeatability, and homogeneous particle size are still difficult to achieve despite tremendous advancements. Nanoparticle properties can be affected by changes in biological extract content, reaction kinetics, and environmental factors [37]. Furthermore, research on the mechanisms underlying biomolecule-mediated reduction and stabilization is still in its early stages [38]. For green nanotechnology to be adopted on an industrial scale, several constraints must be addressed.

Green-fabricated nanoparticles are used in many different industries. Green nanoparticles serve as adsorbents for the removal of heavy metals and photocatalysts for the breakdown of pollutants in environmental remediation [14,22,35].

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They show improved biocompatibility, capability for targeted drug administration, and decreased cytotoxicity in biomedical domains [7,15,40]. Green nanoparticles are used in agriculture as food preservation coatings, antibacterial agents, and nano-fertilizers [19, 23, 32]. The transformational potential of environmentally friendly nanotechnology is demonstrated by these multipurpose roles.

According to recent research, there is a global trend toward sustainable nanomanufacturing, with an emphasis on economical, energy-efficient, and ecologically safe production methods [33, 37]. Green nanotechnology offers long-term ecological and economic benefits and is consistent with the circular economy and sustainable development goals [9,10,33].

Consolidating recent advancements in green synthesis techniques for nanomaterials and nanocomposites, investigating mechanistic insights, assessing fabrication obstacles, and determining future research objectives are therefore imperative. The current study focuses on environmentally benign methods of producing nanoparticles and nanocomposites using plant extracts, microbes, and biopolymers. For the development of sustainable nanomaterials, it also highlights functional applications, characterisation methods, and scale-up issues.

In conclusion, green synthesis has become a revolutionary strategy for sustainable nanotechnology. Eco-friendly fabrication techniques provide high-performance nanomaterials with low environmental impact by substituting hazardous chemicals with biological resources, lowering energy usage, and improving material biodegradability. The importance of green nanomaterials and nanocomposites in tackling global technical and environmental concerns will be further strengthened by ongoing developments in mechanistic knowledge, process optimization, and industrial translation.

II. PRINCIPLES OF GREEN SYNTHESIS AND SUSTAINABLE NANOFABRICATION

Green synthesis of nanomaterials, which is founded on sustainability and environmental responsibility, aims to reduce or eliminate the usage of hazardous chemicals while still efficiently creating functional nanostructures. The core of this technique is the selection of non-toxic reagents and solvents, which ensures that the synthesis process does not produce harmful byproducts that could endanger human health or the environment. In contrast to conventional chemical procedures, which can rely on strong reducing agents or organic solvents, green synthesis uses safe alternatives like water, plant extracts, or naturally occurring compounds to make nanoparticles in a safer and more environmentally friendly manner.

Another key concept is the use of energy-efficient processes, which are often performed at room temperature and pressure. This lowers the energy input required for nanoparticle manufacturing, in sharp contrast to traditional methods that often require high temperatures, prolonged heating, or high-pressure reactors.

By using mild reaction conditions, green synthesis preserves the structural integrity and functionality of sensitive biomolecules or nanocomposite matrices while conserving energy. Another essential element of green synthesis is the utilization of renewable biological precursors such plant extracts, microorganisms, algae, and biopolymers. These biological systems contain naturally occurring reducing and stabilizing chemicals such as phenolics, flavonoids, polysaccharides, and enzymes that help reduce metal ions and control nanoparticle production. The intrinsic capping and stabilization of the biomolecules prevent aggregation and provide a uniform particle size distribution without the need for additional chemical stabilizers.

Recyclability and waste reduction are two further principles of green synthesis. Processes are designed to generate as little waste as possible, and any residual biomass or solvent is often reusable or biodegradable. In line with the circular economy idea, this lessens the impact on the environment and enhances the overall sustainability of nanoparticle production. Finally, the biological mediation of nanoparticle creation enables a simple, one-pot process that integrates reduction, stabilization, and sometimes functionalization into a single phase.

Plant extracts, bacterial cultures, or fungal filtrates eliminate the need for many chemical reagents and complex purification processes by simultaneously serving as reducing agents, stabilizers, and templates. Because this one-pot method not only simplifies the process but also avoids the introduction of hazardous chemicals, green synthesis is a very environmentally friendly method for producing nanomaterials and nanocomposites.

III. GREEN SYNTHESIS STRATEGIES FOR NANOMATERIALS

3.1 Plant-Mediated Synthesis

Plant-mediated synthesis of nanomaterials is one of the most thoroughly studied eco-friendly techniques due to its simplicity, cost, and environmental friendliness. Among the numerous phytochemicals present in plants that have dual roles as stabilizers and reducing agents are flavonoids, terpenoids, phenolic compounds, alkaloids, and polysaccharides. These naturally occurring substances produce nanoparticles with precise size, shape, and outstanding stability by promoting the conversion of metal ions into zero-valent nanoparticles and preventing their aggregation. This technique often entails combining plant extracts, such as leaves, peels, roots, flowers, or seeds, with aqueous solutions of metal salts under mild reaction conditions. By reducing the metal ions to their nanoparticle forms and capping them, the phytochemicals offer a protective coating that enhances biocompatibility. The resulting nanoparticles often have favourable properties such a uniform size distribution, outstanding stability, and surface functional groups that can be further modified for specific applications. [2] Numerous studies have demonstrated the effectiveness of plant-mediated synthesis in producing metallic nanoparticles with beneficial properties. For instance, silver nanoparticles (AgNPs), which have strong antibacterial action against a range of dangerous bacteria and fungi, are made from Azadirachta indica (neem) leaf extract. In a similar vein, Citrus sinensis (orange) peel extract is used to create gold nanoparticles (AuNPs), which have special optical properties like strong surface plasmon resonance that make them suitable for use in drug administration, biosensing, and biomedical imaging [11,13].

There are numerous advantages to plant-mediated synthesis. This strategy is cost-effective and scalable because to the abundance and renewability of plant resources. Because the process is conducted in mild, non-toxic conditions and doesn't require a lot of energy, organic solvents, or hazardous chemicals, it is environmentally friendly. Furthermore, the produced nanoparticles are usually biocompatible, which is essential for culinary and medical applications. Despite these benefits, standardizing plant-mediated synthesis remains challenging. The variety of plant metabolite profiles, which are influenced by factors like plant species, geographic location, harvest season, and extraction process, may lead to variations in nanoparticle size, shape, and yield. Reproducibility and scalability at the industrial level require rigorous optimization of reaction conditions and standardization of plant extracts. However, ongoing research and advancements in process control, which continue to enhance its reliability and application, support the potential of this green synthesis strategy as a sustainable way for manufacturing nanomaterials.

3.2 Microbial Synthesis

Microbial synthesis provides a versatile and sustainable way to produce nanomaterials by leveraging the natural metabolic and enzymatic capabilities of microorganisms like bacteria, fungi, and algae. The extracellular and intracellular enzymes of bacteria serve as biological factories in this process, stabilizing and mediating the reduction of metal ions into nanoparticles. These biological processes provide precise control over particle nucleation and growth, resulting in nanostructures with superior functional properties and constant size and shape [11,16]. Fungi have been widely exploited in the production of metallic nanoparticles due to their high metal tolerance, rapid growth, and capacity to produce several extracellular enzymes. For instance, fungal-mediated synthesis of gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs) has demonstrated the capacity to generate incredibly uniform nanoparticles with narrow size distributions, which are ideal for use in catalysis, drug administration, and biosensing [11, 30]. Similarly, magnetic iron oxide nanoparticles ($Fe3O4$) are produced by bacteria and are particularly useful in biomedical applications such as targeted drug delivery and magnetic resonance imaging (MRI) due to their superparamagnetic properties and biocompatibility [16]. Furthermore, by providing natural reducing agents and capping chemicals that create stable nanoparticles suitable for industrial and environmental applications, algae offer a scalable and eco-friendly alternative. The microbial technique offers several advantages over conventional chemical synthesis. It allows for highly controlled particle shape, tunable size distribution, and enhanced stability without the need of dangerous stabilizers or reducing agents. Furthermore, microbial synthesis can integrate many steps of functionalization into a single process, producing nanoparticles immediately suitable for use in catalytic, pharmacological, or environmental applications [11,19]. However, there are

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certain challenges with microbial synthesis. Strict growing conditions, including controlled pH, temperature, feed availability, and sterile surrounds, are required to maintain microbial viability and reproducibility. Culture conditions must be carefully regulated and standardized because differences in microbial strains and metabolic activity might affect the production and homogeneity of nanoparticles. Despite these limitations, advances in microbial biotechnology and bioprocess engineering continue to enhance the feasibility and expandability of this green synthesis approach. All things considered, microbial synthesis provides a precise, sustainable, and environmentally benign way to produce valuable nanomaterials. In keeping with the overarching goals of green chemistry and nanotechnology, scientists can use the innate metabolic machinery of microbes to create nanoparticles and nanocomposites with particular properties for a range of industrial, biomedical, and environmental applications [16,30].

3.3 Biopolymer-Assisted Green Synthesis

Natural polymers like chitosan, cellulose, starch, alginate, gelatin, and lignin are excellent green templates and matrices for the production of nanomaterials. These biopolymers may be used as structural supports, stabilizers, or reducing agents when making nanocomposites.

Biopolymer-based synthesis increases the mechanical strength, thermal stability, and biodegradability of nanocomposites while reducing environmental toxicity. These materials are especially promising for biomedical devices, sustainable packaging, and environmental remediation technologies.

3.4 Green Physical Methods

By incorporating nanoparticles into a matrix to enhance functionality, advanced materials known as nanocomposites integrate the unique characteristics of both components. When nanoparticles are added to bio-derived polymer matrices, the resulting nanocomposites can exhibit synergistic properties such improved mechanical strength, thermal stability, antibacterial activity, and optical or electrical capabilities. Green synthesis of nanocomposites stresses the use of renewable biopolymers, mild reaction conditions, and environmentally safe methods to produce materials that are both sustainable and high-performing [1,17]. One of the methods that has been thoroughly researched is the integration of metallic nanoparticles with cellulose-based matrices. For example, adding silver nanoparticles to cellulose nanocrystals (Ag/CNC) produces nanocomposites with potent antibacterial activity, making them suitable for biological applications, coatings, and packaging. The cellulose matrix not only offers structural support but also acts as a stabilizing scaffold that enhances biocompatibility and biodegradability while preventing the agglomeration of nanoparticles [17]. In a similar vein, green synthesis techniques have been used to make ZnO/chitosan hybrid films, which are versatile materials with antibacterial, UV-protective, and biodegradable properties. While chitosan, a naturally occurring biopolymer, serves as a matrix and stabilizer, zinc oxide nanoparticles offer antibacterial and UV-blocking qualities. These hybrid films have demonstrated the versatility of green-fabricated nanocomposites and have showed promise in wound healing, food packaging, and cosmetics [25,26]. Another effective tactic is graphene oxide (GO)/cellulose composites, in which graphene oxide is reduced in a cellulose matrix using eco-friendly methods. These nanocomposites have remarkable mechanical strength, electrical conductivity, and barrier properties, and they do away with the requirement for hazardous reducing chemicals that are frequently utilized in chemical reduction procedures. These materials are suitable for application in filtration, electronics, and packaging because they may be manufactured utilizing plant extracts or other green reductants in a biocompatible and environmentally friendly manner [6,9]. In order to further enhance sustainability, green nanocomposite fabrication increasingly employs solvent-free and mechanochemical techniques that reduce the use of volatile organic compounds (VOCs) and energy consumption. By combining nanoparticles and polymers under mechanical pressures like grinding or milling, mechanochemical methods enable tight mixing and chemical interaction without the need of dangerous solvents [3]. In addition to being in line with green chemistry principles, these techniques improve reproducibility, reduce their adverse environmental effects, and facilitate scale-up.

All things considered, green synthesis of nanocomposites offers a great way to produce multifunctional, cost-effective, and environmentally safe materials. By mixing bio-derived polymers with nanoparticles, researchers can produce

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materials that meet specific application requirements while adhering to sustainability standards. This approach demonstrates how green nanotechnology can transform the manufacturing of industrial, pharmaceutical, and environmental materials without compromising environmental safety [1,9,17].

4. Eco-Friendly Fabrication of Nanocomposites

In nanocomposites, which are multiphase materials, nanoscale fillers are dispersed throughout a matrix to produce synergistic properties. Green nanocomposite production relies heavily on non-toxic processing methods, renewable fillers, and biodegradable polymers. Common eco-friendly nanocomposites include clay-reinforced biodegradable polymers, cellulose-based nanocomposites, chitosan/metal oxide nanocomposites, and biopolymer/metal nanoparticle composites. Green manufacturing techniques such in situ synthesis, solution casting, melt blending with bio-polymers, and solvent-free processing are widely employed to produce sustainable nanocomposites.

5. Characterization of Green-Synthesized Nanomaterials

IV. CHARACTERIZATION TECHNIQUES

The successful manufacture of green-synthesized nanomaterials and nanocomposites requires careful characterization to confirm their structural, chemical, and functional properties in addition to eco-friendly synthesis methods. Precise characterisation provides information about the potential applications of the material, ensures reproducibility, and validates the efficacy of the green synthesis method. A mixture of spectroscopic, diffraction, and microscopic techniques is often utilized to gain a comprehensive understanding of the generated nanomaterials [4,6]. UV-Visible (UV-Vis) Spectroscopy is one of the most widely used techniques for monitoring the growth and stability of nanoparticles. Metal nanoparticles, such as silver and gold, exhibit characteristic surface plasmon resonance (SPR) peaks in the UV-Vis spectrum that can be used to ascertain the particles' size, shape, and concentration. The first non-invasive method utilized in green synthesis to confirm the production of nanoparticles and enhance reaction parameters like extract concentration, pH, and reaction time is UV-Vis spectroscopy [13,31]. X-ray diffraction (XRD) provides detailed information about the average particle size, phase purity, and crystalline structure of nanoparticles. By analysing the diffraction patterns, researchers may determine whether the generated nanomaterials have the necessary crystalline phases. For applications that require certain electrical, optical, or catalytic characteristics, this is essential. Furthermore, XRD helps verify that the nanoparticles are not amorphous and that the green synthesis technique produced well-defined crystalline structures [12,14]. Electron microscopy, especially transmission electron microscopy (TEM) and scanning electron microscopy (SEM), provides a detailed view of the shape, size distribution, and aggregation state of nanoparticles. SEM provides high-resolution photographs of the surface topology, whereas TEM may display lattice fringes and inner features at the nanoscale. Combining these approaches is crucial for assessing how green synthesis processes affect the size uniformity, shape, and dispersion of particles inside polymer matrices or other composite materials [4,8]. Fourier-Transform Infrared (FTIR) Spectroscopy is used to identify functional groups on the surface of nanomaterials, which often originate from the biological precursors utilized in green synthesis. FTIR research verifies that plant phytochemicals, microbial metabolites, or polymeric matrix effectively cap and stabilize nanoparticles. Understanding surface functionalization is necessary to forecast how nanoparticles will interact with biological systems, solvents, or other materials in composite architectures [1,17]. Combining these characterization techniques provides a thorough evaluation of green-synthesized nanomaterials. In addition to verifying the successful manufacturing of nanoparticles, they offer crucial details regarding their chemical composition, structural integrity, and functional properties. By combining spectroscopic, diffraction, and microscopic studies, researchers can improve green synthesis processes, ensure reproducibility, and tailor nanomaterials for specific applications such as antimicrobial coatings, UV-protective films, drug delivery systems, or environmental cleanup [4,6,9].

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V. APPLICATIONS OF GREEN NANOMATERIALS AND NANOCOMPOSITES

Green-synthesised nanoparticles and nanocomposites are now incredibly versatile materials with applications in the medicinal, environmental, and energy sectors. Their adaptable functional properties, inherent biocompatibility, and environmentally friendly production make them ideal candidates for sustainable technology solutions.

5.1 Biomedical Applications

Among the biggest advantages of green-synthesized nanomaterials are their reduced toxicity and biocompatibility, which are crucial for biomedical applications. Metal nanoparticles like silver (AgNPs) have potent antibacterial and antifungal qualities that make them useful in wound dressings, medical device coatings, and antimicrobial compositions [1,18]. By reducing cytotoxicity without compromising antibacterial effectiveness, the capping agents of these nanoparticles which are made from microbes or plants improve their safety profile. Green-synthesized magnetic nanoparticles have been extensively studied in targeted medication delivery systems. Functionalized iron oxide ($Fe3O4$) nanoparticles can be targeted to specific tissues using external magnetic fields, allowing for localized drug release and reducing side effects commonly associated with systemic drug administration [16,19]. additionally, photothermal therapy for cancer has made use of green-produced gold nanoparticles (AuNPs). By absorbing near-infrared light and converting it into heat, AuNPs' unique optical properties particularly surface plasmon resonance allow them to destroy cancer cells with the least amount of damage to surrounding healthy tissue [11,13]. These applications highlight the potential use of green-synthesised nanomaterials in therapeutic, diagnostic, and regenerative medicine.

5.2 Environmental Remediation

Green-synthesized nanomaterials have also demonstrated remarkable success in environmental cleanup by using their huge surface area and catalytic properties to degrade or remove pollutants. Titanium dioxide (TiO□) nanoparticles derived from plant extracts have demonstrated efficient photocatalytic degradation of organic pigments and contaminants in wastewater under mild conditions. By employing biologically derived reducing agents, which stop additional chemical contamination, the process is kept environmentally safe [14]. Magnetically separable nanocomposites such as $Fe3O4$ in combination with biopolymers or metal oxides have made it possible to rapidly remove heavy metals such as lead, cadmium, and arsenic from water. These nanocomposites are easy to recover thanks to external magnets, which improves recyclability and reduces secondary pollution [6,23]. Because of their high reactivity, simplicity of separation, and environmentally benign production, green nanoparticles are positioned as sustainable alternatives for pollution remediation and water purification.

5.3 Energy Storage and Conversion

Green synthesis techniques are also revolutionizing energy storage and conversion technology. Bio-derived carbon nanomaterials, such as carbon nanotubes (CNTs) made from plant biomass or agricultural waste, are ideal for supercapacitors and electrode materials due to their high conductivity, large surface area, and remarkable chemical stability [6,9]. These renewable carbon sources reduce dependency on materials derived from fossil fuels, which is consistent with the concepts of green chemistry. Green-synthesized graphene and graphene oxide composites, which provide enhanced electron transport, energy density, and cycle stability, are also being used in high-performance batteries and fuel cells. Using plant extracts or microbial systems, ecologically friendly reduction processes eliminate toxic chemicals often required in chemical graphene reduction, resulting in sustainable and biocompatible materials suitable for large-scale energy applications [6,9]. Green nanoparticles' versatility from biological therapeutics to environmental cleanup and energy applications—highlights their potential as sustainable, high-performance materials. By integrating state-of-the-art material design with eco-friendly synthesis methods, researchers may produce practical nanoparticles and nanocomposites that meet both technological demands and environmental sustainability goals.

VI. MECHANISTIC INSIGHTS IN GREEN SYNTHESIS

A deep understanding of the concepts behind the synthesis of nanomaterials is necessary to optimize reaction conditions, control nanoparticle properties, and enhance repeatability. Unlike conventional chemical procedures, green synthesis incorporates biological entities such as plant extracts, microbial metabolites, and biopolymers to facilitate the formation of nanoparticles. A redox balance between the metal precursors and the natural reducing agents present in these biological systems typically drives the conversion of metal ions into nanoparticles [2,31].

In plant-mediated synthesis, phytochemicals such as flavonoids, terpenoids, phenolics, and alkaloids serve as electron donors, decreasing metal ions while oxidizing themselves. This electron transfer not only aids in the nucleation of the particles but also modifies their size, shape, and homogeneity. For example, phenolic hydroxyl groups in plant extracts are oxidized and bind to the surface of the nanoparticles to serve as capping agents, preventing aggregation and enhancing colloidal stability when silver or gold ions are reduced [13,17]. Controlling the growth of nanoparticles requires interactions between capping molecules. Plant extracts, polymeric matrices, and microbial exopolysaccharides all contain biomolecules that adsorb onto the surfaces of nanoparticles to provide an electrostatic or steric barrier that prevents agglomeration and regulates further particle growth. This stabilizing mechanism is essential for achieving reproducible properties and constant nanoparticle size distributions, which are critical for industrial, biomedical, and environmental applications [1,16]. Mechanistic investigations have been further clarified through the use of spectroscopic and analytical techniques. Fourier-transform infrared (FTIR) spectroscopy confirms the activity of biomolecules in reduction and capping by detecting functional groups on the surface of nanoparticles. Mass spectrometry can verify that phytochemicals serve as electron donors during the synthesis process by detecting their oxidized versions [4,9]. Our research collectively demonstrates that the green synthesis process is a self-limiting, bio-mediated redox reaction where reduction, nucleation, and stabilization occur simultaneously in a single pot. By understanding these mechanistic insights, researchers may modify synthesis parameters such as pH, temperature, extract concentration, and reaction time to produce nanoparticles with the right size, shape, and functionality. Additionally, knowing the chemical routes makes it easier to logically design hybrid nanocomposites, where a number of biological molecules or polymers can cooperate to influence the stability and synthesis of nanoparticles [17,19]. The interplay between metal precursors and biological reductants, as well as the critical role of capping agents in controlling the properties of nanoparticles, are highlighted by a mechanistic knowledge of green synthesis. By utilizing these insights, scientists can optimize eco-friendly synthesis methods to produce nanomaterials and nanocomposites with reliable, repeatable, and application-specific properties, accomplishing both environmental and technological objectives [1,31].

VII. CHALLENGES AND LIMITATIONS

Although it has many practical and environmental advantages, green synthesis of nanomaterials and nanocomposites is not without challenges. One of the primary issues is reproducibility, which arises from the intrinsic unpredictability of biological precursors. Depending on the species, location, growing conditions, harvest season, and extraction methods, different complex combinations of biomolecules can be discovered in plant extracts, microbial metabolites, and biopolymers. Such heterogeneity may lead to variations in particle size, shape, and functional properties, which can significantly affect the nucleation, growth, and stabilization of nanoparticles [19,31]. Another significant challenge is scaling up green synthesis techniques. For laboratory-scale synthesis, small quantities and regulated reaction conditions are often favourable; nevertheless, translating these methods to industrial-scale manufacture presents challenges. Biological extracts can show batch-to-batch variability, shifting nanoparticle characteristics over time, and changes in reaction kinetics due to their complexity. Maintaining the same level of consistency, yield, and quality at larger volumes requires rigorous standardization and process optimization [1,37]. Furthermore, compared to traditional chemical approaches, mechanistic understanding of green synthesis is still in its infancy. It is challenging to fully understand the complex redox mechanisms, enzyme-mediated reactions, and molecular interactions involved in the biological reduction of metal ions and concomitant stabilization by biomolecules. It may be difficult to precisely regulate the production of nanoparticles and to logically create new nanocomposites due to this lack of mechanistic understanding [38,4].To solve these problems, standardized processes must be established, such as dependable sources of biological material, effective extraction techniques, and reproducible reaction conditions. Furthermore, the integration of advanced analytical tools, such as spectroscopic, chromatographic, and computational techniques, is essential to monitor reaction pathways, confirm nanoparticle properties, and ensure process dependability. These processes are crucial for translating green synthesis from lab research to commercial and industrial applications while maintaining environmental sustainability.

VIII. FUTURE PERSPECTIVES

The future of green nanotechnology depends on the development of hybrid and multi-modal synthesis techniques that combine the benefits of biological systems with state-of-the-art physical or chemical techniques. For example, coupling biopolymer-mediated synthesis with microwave, ultrasonic, or mechanochemical support may increase efficiency and scalability by improving nanoparticle homogeneity, speeding up reactions, and using less energy [5,9]. Advances in computational chemistry and mechanistic modelling are expected to play a major role in the logical design of green-synthesized nanomaterials. Comprehensive computational studies can predict the interactions between biological reductants, capping agents, and metal precursors, providing information about nucleation and growth pathways. Such predictive models can guide experimental conditions, improve repeatability, and make it easier to create nanomaterials with tailored properties for particular uses [4].

The development of large-scale green manufacturing processes is another important avenue for the future. Standardized, commercially viable processes that follow green chemistry principles will enable the sustainable production of nanomaterials and nanocomposites for biomedical, environmental, and energy applications. This means maximizing reaction conditions, cutting waste, ensuring consistent quality, and using sustainable raw materials at industrial scales [1,37]. Finally, multidisciplinary collaboration among chemists, biologists, materials scientists, and engineers will promote innovation in this field. By combining their understanding of biological systems, process engineering, and nanomaterial design, researchers may be able to overcome current limitations and expand the applications of green-synthesized nanomaterials. A sustainable and technologically advanced future is being made possible by the convergence of green chemistry, nanotechnology, and bioengineering to produce next-generation nanomaterials that are both highly effective and environmentally benign [9,19].

IX. CONCLUSION

The green synthesis of nanomaterials and nanocomposites is a sustainable and ecologically friendly way to produce innovative functional materials. By employing the inherent reducing and stabilizing characteristics of biological systems, such as plant extracts, microbial metabolites, and biopolymers, researchers can produce nanoparticles and nanocomposites without the use of hazardous chemicals or energy-intensive processes. In addition to reducing the environmental effect of creating nanomaterials, this technique enhances their safety, biocompatibility, and biodegradability all of which are critical for applications in energy technology, environmental remediation, and medicine [1,31]. the versatility of green synthesis allows for the creation of a wide range of nanomaterials, including metallic nanoparticles, metal oxide nanocomposites, and bio-derived carbon nanostructures. These materials' synergistic properties antibacterial activity, photocatalytic efficiency, UV protection, magnetic responsiveness, and enhanced electrical conductivity make them suitable for multifunctional applications. Plant-mediated, microbial-mediated, and biopolymer-based synthesis technologies enable one-pot, environmentally friendly manufacturing, while mechanochemical and solvent-free methods further reduce the usage of volatile organic compounds and dangerous solvents [9,17].

Notwithstanding these benefits, issues with reproducibility, scale-up constraints, and insufficient mechanistic comprehension persist. To translate laboratory-scale successes into industrial-scale production, these issues will need to be resolved by standardized methodologies, sophisticated characterisation, computer modelling, and hybrid synthesis processes [19,37]. By enabling the creation of tailored nanomaterials with controlled size, shape, and functionality, multidisciplinary collaboration between engineers, chemists, biologists, and materials scientists will accelerate the development of green nanotechnology in the future. By combining high performance capabilities with environmental sustainability, green synthesis provides a path toward industrial-ready, versatile nanomaterials that support innovation while preserving ecological balance.

In conclusion, green synthesis is not only a useful replacement for conventional chemical methods but also a progressive strategy that combines material innovation with ecological practices. Research, improvement, and integration of eco-friendly methods must continue to ensure that nanomaterials and nanocomposites significantly contribute to both technological advancement and environmental stewardship.

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