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Nano Green Chemistry for Sustainable Environmental Remediation: Recent Advances and Future Perspectives

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Abstract

Environmental pollution resulting from rapid industrialization, urbanization, intensive agriculture, and unsustainable resource utilization has become a major global concern requiring innovative, efficient, and environmentally sustainable remediation technologies. Conventional treatment methods often involve high energy consumption, toxic chemicals, secondary waste generation, and limited pollutant removal efficiency. Nano green chemistry has emerged as an interdisciplinary field that combines the principles of green chemistry with nanotechnology to develop environmentally benign nanomaterials and sustainable remediation strategies. Green-synthesized nanoparticles, nanocomposites, bio-based nanomaterials, metal oxides, carbon nanomaterials, and nanocatalysts have demonstrated exceptional potential for removing heavy metals, dyes, pharmaceuticals, pesticides, emerging contaminants, microplastics, and pathogenic microorganisms from contaminated water, soil, and air. Plant extracts, microorganisms, algae, fungi, agricultural wastes, and natural polymers are increasingly utilized as eco-friendly reducing and stabilizing agents for nanoparticle synthesis, minimizing hazardous chemical usage while improving material biocompatibility. Recent advances in photocatalysis, adsorption, membrane technologies, advanced oxidation processes, environmental sensing, and multifunctional nanocomposites have further expanded the applications of nano green chemistry in environmental remediation. This review discusses the fundamental principles, green synthesis approaches, nanomaterial classifications, remediation mechanisms, recent environmental applications, current challenges, and future perspectives of nano green chemistry for sustainable environmental management.

Keywords: *Nano green chemistry, Green nanotechnology, Environmental remediation, Sustainable nanomaterials, Green synthesis, Photocatalysis.*

1. Introduction

Environmental pollution has become one of the most pressing global challenges of the twenty-first century. Rapid industrial development, urban expansion, mining activities, intensive agriculture, pharmaceutical production, textile manufacturing, and improper waste disposal have resulted in the widespread contamination of aquatic, terrestrial, and atmospheric environments. Hazardous pollutants including heavy metals, pesticides, pharmaceuticals, dyes, petroleum hydrocarbons, endocrine-disrupting chemicals, microplastics, and persistent organic pollutants continue to accumulate in ecosystems, threatening biodiversity, human health, food security, and sustainable development. Conventional remediation technologies, although effective in certain applications, often require large quantities of chemicals, consume significant amounts of energy, generate secondary pollutants, and involve high operational costs [1]. Green chemistry, introduced to minimize the environmental impact of chemical processes, emphasizes pollution prevention, renewable resources, safer chemicals, waste minimization, energy efficiency, and environmentally benign synthesis. Simultaneously, nanotechnology has revolutionized material science through the development of nanoscale materials possessing exceptional physicochemical properties, including high surface area, enhanced catalytic activity, tunable surface chemistry, and improved adsorption capacity [2]. The integration of these two disciplines has led to the emergence of nano green chemistry, an innovative field dedicated to designing sustainable nanomaterials using environmentally friendly synthesis methods and applying them to pollution control and environmental restoration. Unlike conventional nanoparticle synthesis, which often relies on hazardous reducing agents and toxic solvents, green synthesis utilizes plant extracts, bacteria, fungi, algae, enzymes, polysaccharides, and agricultural residues as natural reducing and stabilizing agents. These biological systems produce nanoparticles under mild reaction conditions while reducing environmental toxicity and improving biocompatibility [3].

Green nanomaterials have demonstrated remarkable efficiency in wastewater treatment, heavy metal removal, photocatalytic degradation of pollutants, carbon capture, environmental sensing, antimicrobial applications, and soil remediation.

Recent advances in nanocomposite engineering, bio-inspired materials, photocatalysis, membrane technologies, and multifunctional nanomaterials have significantly expanded the practical applications of nano green chemistry. These innovations support global sustainability goals by promoting circular economy principles, waste valorization, renewable resource utilization, and environmentally responsible technological development. This review presents a comprehensive overview of nano green chemistry, focusing on green synthesis methods, classifications of environmentally friendly nanomaterials, pollutant removal mechanisms, environmental applications, recent technological advances, challenges, and future research opportunities.

2. Principles of Nano Green Chemistry

Nano green chemistry integrates the twelve principles of green chemistry with sustainable nanotechnology to minimize environmental impacts throughout the entire life cycle of nanomaterials. The primary objective is to design nanomaterials that are highly efficient in environmental remediation while reducing hazardous chemical consumption, energy requirements, waste generation, and ecological toxicity. This holistic approach emphasizes not only the performance of nanomaterials but also their sustainable production, utilization, recycling, and disposal [4]. One of the fundamental principles involves the use of renewable biological resources as reducing and stabilizing agents during nanoparticle synthesis. Plant extracts rich in flavonoids, phenolic compounds, terpenoids, alkaloids, proteins, and carbohydrates facilitate the reduction of metal ions into stable nanoparticles without requiring toxic synthetic reagents. Similarly, microorganisms such as bacteria, fungi, algae, and yeast possess enzymatic systems capable of producing metal nanoparticles under environmentally benign conditions.

Energy-efficient synthesis represents another important aspect of nano green chemistry. Biological synthesis generally occurs at ambient temperature and pressure, thereby reducing energy consumption compared with conventional chemical and physical synthesis techniques. Water is increasingly employed as the preferred reaction medium, replacing hazardous organic solvents and improving environmental compatibility [6]. Designing biodegradable and low-toxicity nanomaterials constitutes another essential objective. Researchers increasingly prioritize materials that exhibit high remediation efficiency while minimizing adverse effects on ecosystems and human health. Life cycle assessment, ecotoxicological evaluation, and sustainability analysis are therefore becoming integral components of nanomaterial development.

Waste valorization further strengthens the sustainability of nano green chemistry. Agricultural residues, fruit peels, crop wastes, forestry biomass, food processing residues, and industrial by-products serve as inexpensive raw materials for synthesizing nanomaterials, transforming waste into value-added environmental remediation products while supporting circular economy initiatives.

3. Green Synthesis and Classification of Nanomaterials

Green synthesis has become one of the most rapidly expanding areas of nanotechnology because it provides environmentally friendly alternatives to conventional nanoparticle production. Biological systems contain numerous naturally occurring biomolecules capable of reducing metal ions while simultaneously stabilizing the resulting nanoparticles against aggregation. Plant-mediated synthesis is currently the most widely investigated approach due to its simplicity, low cost, rapid reaction rates, and scalability. Extracts obtained from leaves, flowers, fruits, roots, seeds, bark, and medicinal plants contain polyphenols, flavonoids, tannins, proteins, sugars, and organic acids that function as natural reducing and capping agents. Silver, gold, copper, zinc oxide, titanium dioxide, iron oxide, and cerium oxide nanoparticles have all been successfully synthesized using plant extracts [6]. Microbial synthesis utilizes bacteria, fungi, algae, actinomycetes, and yeast to produce nanoparticles either intracellularly or extracellularly. Microorganisms possess enzymes capable of reducing metal ions while controlling nanoparticle size and morphology. Fungal systems are particularly attractive because of their high biomass production and secretion of extracellular enzymes that facilitate nanoparticle recovery [7]. Green nanomaterials employed in environmental remediation include metallic nanoparticles, metal oxide nanoparticles, carbon-based nanomaterials, polymeric nanocomposites, magnetic nanoparticles, biochar nanocomposites, metal-organic frameworks (MOFs), cellulose nanomaterials, and hybrid multifunctional composites. Metal oxide nanoparticles such as titanium dioxide, zinc oxide, iron oxide, manganese oxide, and cerium oxide exhibit excellent photocatalytic and adsorption properties. Carbon nanomaterials including graphene oxide, reduced graphene oxide, carbon nanotubes, activated carbon, and biochar-based nanocomposites possess exceptionally high surface areas suitable for pollutant adsorption and catalytic degradation. Recent developments emphasize multifunctional nanocomposites that combine adsorption, catalysis, antimicrobial activity, magnetic separation, and environmental sensing within a single material platform. Such integrated systems significantly enhance remediation efficiency while simplifying recovery and reuse.

Table 1: Green-Synthesized Nanomaterials for Environmental Remediation

Nanomaterial	Green Synthesis Source	Major Environmental Applications
Silver nanoparticles	Plant extracts, fungi	Antimicrobial water treatment
Gold nanoparticles	Medicinal plants	Environmental sensing
Zinc oxide nanoparticles	Plant metabolites	Photocatalytic degradation of dyes
Titanium dioxide nanoparticles	Plant extracts	Organic pollutant degradation
Iron oxide nanoparticles	Bacteria, algae	Heavy metal removal and magnetic separation
Biochar nanocomposites	Agricultural biomass	Wastewater treatment and soil remediation
Graphene oxide composites	Green reducing agents	Adsorption of organic contaminants
Cellulose nanomaterials	Agricultural waste	Sustainable filtration membranes

4. Mechanisms of Environmental Remediation by Green Nanomaterials

The exceptional remediation efficiency of green-synthesized nanomaterials is primarily attributed to their unique physicochemical properties, including high specific surface area, abundant active sites, tunable surface chemistry, excellent catalytic activity, and enhanced electron transfer capabilities. Unlike conventional remediation materials that often rely on a single removal mechanism, green nanomaterials simultaneously employ multiple physicochemical and biological processes to eliminate contaminants from environmental matrices. These mechanisms include adsorption, photocatalytic degradation, redox reactions, ion exchange, precipitation, membrane filtration, antimicrobial activity, and advanced oxidation processes [8]. Adsorption remains one of the most important mechanisms responsible for pollutant removal. Nanomaterials possess exceptionally large surface areas and abundant functional groups such as hydroxyl, carboxyl, amino, and carbonyl groups that facilitate the adsorption of heavy metals, dyes, pesticides, pharmaceutical residues, antibiotics, and endocrine-disrupting chemicals. Electrostatic attraction, hydrogen bonding, hydrophobic interactions, and π–π interactions further enhance adsorption efficiency toward various organic pollutants.

Photocatalysis represents another major remediation mechanism.

Semiconductor nanoparticles such as titanium dioxide (TiO_2), zinc oxide (ZnO), and cerium oxide (CeO_2) absorb ultraviolet or visible light and generate electron–hole pairs capable of producing highly reactive oxygen species, including hydroxyl radicals (OH), superoxide radicals (O_2−), and hydrogen peroxide. These reactive species oxidize complex organic contaminants into simpler, less toxic compounds or completely mineralize them into carbon dioxide and water [9]. Redox reactions also contribute significantly to contaminant degradation. Iron-based nanoparticles, particularly nanoscale zero-valent iron (nZVI), reduce toxic metal ions and chlorinated organic compounds into environmentally benign products. Simultaneously, magnetic nanomaterials facilitate rapid recovery after pollutant removal, improving material recyclability and reducing secondary environmental contamination.

Antimicrobial activity is another important characteristic of green nanomaterials. Silver, copper oxide, and zinc oxide nanoparticles inhibit microbial growth through membrane disruption, oxidative stress induction, protein denaturation, and DNA damage. These properties make green nanomaterials valuable for water disinfection and pathogen removal [10]. The integration of adsorption, catalysis, and antimicrobial functions within multifunctional nanocomposites has significantly improved remediation efficiency and broadened the practical applications of nano green chemistry in sustainable environmental management.

Table 2: Major Environmental Remediation Mechanisms of Green Nanomaterials

Mechanism	Target Pollutants	Major Function
Adsorption	Heavy metals, dyes, pharmaceuticals	Surface binding and pollutant removal
Photocatalysis	Organic contaminants	Oxidative degradation
Advanced oxidation	Persistent pollutants	Mineralization into harmless products
Redox reactions	Toxic metal ions	Chemical transformation
Ion exchange	Heavy metals	Replacement of toxic ions
Antimicrobial activity	Pathogenic microorganisms	Water disinfection
Magnetic separation	Mixed contaminants	Rapid recovery and reuse

5. Environmental Applications of Nano Green Chemistry

Green nanotechnology has transformed environmental remediation by providing sustainable solutions for water purification, soil restoration, air pollution control, waste management, environmental monitoring, and renewable energy production. The multifunctional properties of green-synthesized nanomaterials enable efficient removal of diverse contaminants while minimizing environmental impacts associated with conventional remediation technologies [11]. Water treatment represents the most extensively investigated application of nano green chemistry. Green nanomaterials effectively remove heavy metals such as lead, cadmium, mercury, chromium, arsenic, and nickel through adsorption, reduction, and precipitation mechanisms. They also degrade pharmaceutical residues, pesticides, dyes, endocrine-disrupting chemicals, antibiotics, and other emerging contaminants through photocatalysis and advanced oxidation processes. Biochar-based nanocomposites, graphene oxide, magnetic nanoparticles, and metal oxide nanomaterials have demonstrated excellent performance in wastewater treatment owing to their high adsorption capacities and regeneration potential. In soil remediation, green nanomaterials immobilize toxic metals, degrade persistent organic pollutants, improve nutrient availability, and stimulate beneficial microbial activity. Iron oxide nanoparticles, biochar nanocomposites, and nano-hydroxyapatite effectively reduce the bioavailability of heavy metals while restoring soil fertility and supporting sustainable agricultural production. Plant-mediated nanoparticles further contribute to phytoremediation by enhancing plant growth and increasing contaminant uptake. Air pollution control has emerged as another important application area. Titanium dioxide, zinc oxide, graphene-based materials, and photocatalytic nanocomposites efficiently degrade volatile organic compounds (VOCs), nitrogen oxides, sulfur oxides, and airborne microorganisms. Photocatalytic coatings applied to building materials and filtration systems continuously remove atmospheric pollutants under natural sunlight, contributing to improved urban air quality [12]. Nano green chemistry also plays an increasingly important role in environmental sensing and monitoring. Green-synthesized nanosensors exhibit exceptional sensitivity and selectivity for detecting heavy metals, pesticides, pharmaceutical residues, pathogenic microorganisms, and toxic gases. Integration with artificial intelligence and wireless monitoring systems enables real-time environmental surveillance and rapid contamination assessment. Furthermore, green nanomaterials contribute to renewable energy and circular economy initiatives by supporting hydrogen production, carbon capture, biomass conversion, waste valorization, and energy storage technologies. Their multifunctionality makes them valuable components of sustainable environmental management strategies.

Table 3: Major Applications of Green Nanomaterials in Environmental Remediation

Application Area	Representative Nanomaterials	Major Environmental Benefits
Wastewater treatment	Biochar nanocomposites, graphene oxide	Removal of heavy metals and organic pollutants
Soil remediation	Iron oxide nanoparticles, nano-hydroxyapatite	Immobilization of contaminants
Air purification	TiO_2, ZnO photocatalysts	Degradation of airborne pollutants
Water disinfection	Silver nanoparticles	Elimination of pathogenic microorganisms
Environmental sensing	Graphene-based nanosensors	Rapid pollutant detection
Carbon sequestration	Biochar nanocomposites	Climate change mitigation
Renewable energy	Nanocatalysts	Sustainable energy production

6. Challenges and Future Perspectives

Despite remarkable advances, several scientific, technological, and regulatory challenges remain before nano green chemistry can achieve widespread commercial implementation. One of the primary concerns involves the long-term environmental fate and ecotoxicity of engineered nanomaterials. Although green synthesis reduces the use of hazardous chemicals, the environmental behavior, persistence, transformation, and bioaccumulation of nanoparticles require comprehensive investigation to ensure ecological safety. Another significant challenge is large-scale production. Many laboratory-scale green synthesis methods exhibit limited reproducibility, inconsistent particle size distribution, and difficulties in process standardization. Variability in biological reducing agents, plant metabolites, and microbial systems can influence nanoparticle properties, making industrial-scale manufacturing challenging [13]. Economic considerations also affect commercialization. Although biological synthesis is environmentally friendly, large-scale extraction of plant metabolites, purification of nanoparticles, quality control, and storage remain relatively expensive. Developing continuous, automated, and cost-effective synthesis technologies will therefore be essential for industrial adoption. Future research should focus on designing biodegradable nanomaterials with minimal ecological risks while maximizing remediation efficiency. Artificial intelligence, machine learning, computational chemistry, and molecular modeling are expected to accelerate the rational design of next-generation nanomaterials with optimized physicochemical properties. Hybrid systems integrating photocatalysis, adsorption, membrane technologies, electrochemical treatment, and biological remediation are likely to dominate future environmental applications.

7. Conclusion

Nano green chemistry has emerged as a transformative interdisciplinary field that integrates the principles of green chemistry with advanced nanotechnology to develop sustainable solutions for environmental remediation. By utilizing renewable biological resources such as plant extracts, microorganisms, algae, fungi, and agricultural residues for nanoparticle synthesis, green nanotechnology minimizes hazardous chemical usage while producing highly efficient functional nanomaterials with superior adsorption, catalytic, antimicrobial, and sensing properties. Recent advances in green-synthesized metallic nanoparticles, metal oxide nanomaterials, carbon-based nanocomposites, magnetic nanoparticles, biochar composites, and multifunctional hybrid materials have significantly expanded environmental applications in water purification, soil remediation, air pollution control, wastewater treatment, environmental monitoring, and carbon sequestration. Their ability to remove heavy metals, pharmaceuticals, pesticides, dyes, microplastics, pathogens, and emerging contaminants through adsorption, photocatalysis, redox reactions, and advanced oxidation processes demonstrates their immense potential for sustainable pollution management. Despite these promising developments, challenges associated with nanoparticle ecotoxicity, environmental fate, production scalability, standardization, economic feasibility, and regulatory approval remain important areas for future investigation, nano green chemistry represents a key enabling technology for sustainable environmental remediation and circular bioeconomy development. Its continued advancement will contribute substantially to pollution reduction, ecosystem restoration, resource conservation, climate resilience, and the global transition toward environmentally responsible and sustainable technological innovation.

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