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ARTICLE

Green Nanotechnology for Environmental Sensing and Monitoring

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ABSTRACT

Environmental degradation driven by industrialization, urban expansion, and agricultural intensification demands advanced, sustainable monitoring tools capable of detecting contaminants at trace levels. Green nanotechnology—rooted in the principles of green chemistry—offers a pathway to develop high-performance environmental sensing systems while minimizing ecological and human health risks. This review examines the principles of green nanotechnology, emphasizing eco-friendly synthesis routes, life cycle considerations, and their influence on nanomaterial properties relevant to sensing. It scans the principal categories of nanomaterials (grassroots) synthesized with green methods, which include metal, metal oxide, carbon-based, and polymer frameworks, and their incorporation into optical, electrochemical, and mass-based sensitive systems. Examples of applications include water, air, soil, and climate-related monitoring, as well as technical, environmental, economic, and policy issues shaping their future adoption. New technologies emerging on the horizon include hybrid nanomaterials, biodegradable platforms, and AI-augmented data analysis, indicating the age of new sustainable monitoring systems. Green nanotechnology can therefore be termed an intersection between technological innovation and environmental care, involving real-time sensing with complete environmental conservation.

Keywords: Green Nanotechnology; Environmental Sensing; Eco-Friendly Synthesis; Sustainable Monitoring; Nanomaterials

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1. Introduction

The world is in the 21st century, a period that has never been environmentally challenging. High rates of air, water, and soil pollution have occurred because of rapid industrialization, over urbanization, and intensive agricultural activities. At the same time, climate change is increasing the severity of extreme weather events, intensifying ecosystem disruption, and increasing environmental degradation. These adversities demand strong, precise, and real-time monitoring mechanisms that are able to notice environmental risks at trace mass before they transform into big-scale crises. Key to this mission are environmental sensing and monitoring technologies: the environmental protection equivalent of eyes and ears. They give important information and data to policymakers, industrial operators, researchers, and communities to make informed and prompt action ^[1,2].

Nanotechnology has become an influential instrument in this field over the last 20 years. Nanomaterials have an outstanding physicochemical property (they possess a high surface volume ratio, have adjustable optical and electronic properties, and chemical reactivity that exceeds that of the corresponding bulk materials), so the detection systems designed with their utilization can achieve a previously unachievable sensitivity and selectivity. Nanomaterial sensors can detect pollutants at far lower concentrations (several orders of magnitude) than conventional techniques, and due to their very small size, can respond rapidly and potentially be miniaturized and carried around. However, as the manufacturing and application of nanomaterials become extensive, the question of the environmental and health effects of their manufacture and disposal has come into focus. The normal route of nanomaterial manufacturing typically relies on toxic chemicals, demands significant amounts of energy, and uses non-sustainable starting materials—ironically, making these methods significantly contribute to the same environmental pressures these technologies claim to help solve ^[3].

This apparent contradiction has created an interest in green nanotechnology, a field that combines the performance benefits of nanomaterials with the concepts of sustainability and environmental stewardship. Green nanotechnology pursues sustainable designs, synthesizes and

uses nanomaterials in a way that minimizes resource use, decreases hazardous wastes, and reduces environmental impact throughout the life cycle of the entire material. The idea is similar to the “12 Principles of Green Chemistry,” which promote renewable raw materials, more benign solvents, energy efficiency, and the making of inherently non-toxic materials. Within this framing of environmental sensing, attention is given not only to the sensing of pollutants, but also to the responsible production of the sensing materials themselves ^[2,4].

An increasing amount of evidence shows that environmentally friendly synthesis pathways may lead to the production of nanomaterials that perform at least as well, or even better, than those produced using conventional materials and processes. Such biological methods of synthesis, e.g., using extracts of plants, microorganisms, or enzymes, allow nanoparticle formation to occur without complicated reducing agents or stabilizers and thus without harsh chemicals. Similarly, other emerging techniques, such as low-temperature, solvent- and microwave-assisted syntheses, limit the energy requirements and amount of solvent wasted. The risks are minimized in such techniques, which can be scaled up with fewer occupational hazards and environmental liabilities. Also, the biocompatibility of the green-synthesized nanomaterials tends to be better, offering opportunities to safely apply them in drinking water, agricultural soils, and urban airspace ^[5].

Incorporation of green nanotechnology in environmental sensing and monitoring has come at a strategic time and for good reasons. To begin with, the scope and complexity of global environmental monitoring networks are growing. This growth might be due to international climate agreements and public demands for transparency through stricter environmental regulations. Second, with the advent of the Internet of Things (IoT) and wireless sensor networks, continuous and distributed monitoring needs cost-effective, elastic, and secure sensing facilities. Third, with sustainability becoming a primary condition for implementing technological adoption, industries and governments are willing to consider materials and devices that have combined performance and environmental responsibility ^[6-8].

Green nanotechnology has a wide variety of environmental sensing applications. Green-synthesized nanopar-

ticles have also been adapted in the speedy detection of heavy metallic elements such as lead, mercury, and arsenic in water quality indication, nutrients such as nitrates and phosphates, pesticides, and also pathogenic organisms. Nanostructured metal oxides and bio-derived carbon materials have been used to achieve remarkable sensitivity in volatile atmospheric monitoring of volatile organic compounds (VOCs), nitrogen oxides, sulfur dioxide, and particulate matter. In the case of soil monitoring, they have been incorporated into handheld devices containing bio-synthesized nanomaterials, enabling the detection of agrochemical residues, hydrocarbon-contaminated soil, and other industrial contaminants. In addition to pollution sensing, green nanotechnology is being utilized in climate-related monitoring processes, such as monitoring of greenhouse gases and changes in atmospheric chemistry^[2,9].

An important characteristic of such applications is that they are not independent. The shift to multimodal sensing and data analytical capabilities is increasingly used to overcome the limitations of discrete environmental sensing systems, such as optical, electrochemical, and mass-based modalities, coupled with detailed data analytics and AI algorithms to make sense of complex environmental data. The green nanomaterials are showing to be flexible to these hybrid platforms, allowing multifunctional, miniaturized, and even biodegradable sensors. As an example, food-waste synthesized carbon quantum dots can be designed to fluoresce in the presence of certain contaminants, whereas zinc oxide nanorods made using green-based synthesis have shown promise as the sensing mechanism behind low-power gas sensors. In others, the synthesis process itself has given the material a special surface chemistry or defect structure, which improves the sensing capability, showing that being environmentally responsible does not have to be tied to loss of technological performance^[10,11].

Notwithstanding these promising appurtenances, green nanotechnology as a sensing environmental application faces challenges. Reproducibility and the uniformity of materials used can be influenced by variabilities in biological and low-impact methods of synthesis. The scale-up of some green synthesis methods raises questions, particularly regarding cost competitiveness with current industrial technology. Moreover, green synthesis does not remove all

possible risks related to the use and disposal of nanoparticles, highlighting the necessity to conduct thorough nanotoxicology studies and develop the specific regulatory measures for green nanomaterials. Such considerations emphasize the need to use a life cycle approach, including sourcing and life cycles of raw materials, fabrication of the device, deployment, and end-of-life^[12,13].

The urgency of monitoring the environment and the need to support it with environmentally-friendly and sustainable technologies offer a chance to critically review green nanotechnology as an approach to environmental sensing and monitoring systems, which is certainly timely and useful. This article attempts such a review, touching on the following main topics: the principles and practices of green synthesis of nanomaterials; the nature of nanomaterials used in sensing; the mechanisms and technologies that make sensing of the environment possible; the applications in the real world (water, air, soil, climate sensing), the issues, and the way ahead. The review aims to guide the future development of environmentally responsible sensing technologies by synthesizing existing knowledge and identifying emerging trends, enabling scientists, engineers, policymakers, and industry stakeholders to develop these types of sensing tools^[2,14].

Overall, it can be said that the area of green nanotechnology is a union of two important scientific trends: the search for superior environmental and monitoring solutions and the necessity of creating technology, that would not question the ecological integrity. Once successfully implemented, it can reinvent environmental sensing, shifting it out of its status as a mere diagnostic instrument into a paradigm of sustainable innovation, one that can safeguard the planet and serve as an example of the environmental responsibility that it advocates. Below, the fundamental principles, materials, processes, and usages are explored that characterise this fast-developing field.

2. Principles of Green Nanotechnology

Nanotechnology Green nanotechnology can be thought of as a combination of nanoscience and environmental sustainability values. It is not only focused on the use of the exceptional characteristics of nanomaterials—

such as their high surface area, high reactivity, and tunable optical and electronic properties—but also on their design and production, ensuring they do not create adverse consequences on ecosystems or human health once discarded. This strategy does not end with producing a cleaner nanotechnology; it also aims to recreate the entire lifecycle of the material. The goal is for all stages, from raw material selection to end-of-life management, to minimize waste, use resources efficiently, and avoid toxic inputs. By doing so, it remains very close to the spirit of green chemistry and modifies it to the nanoscale, ensuring that the positive effects of nanotechnology can be achieved with minimal new pressures on the environment ^[2,15,16].

2.1. Translating Green Chemistry Principles to Nanotechnology

Green chemistry application to nanotechnology requires making the commitment that the potential damage to the environment be prevented at the source, as opposed to corrective action after the fact. This necessitates the selection of synthesis routes that do not use hazardous reagents, thereby minimizing or completely bypassing chemical detoxification of the product after manufacture. Substitution of non-renewable feedstocks with renewable ones, such as an extract of a plant, agricultural residues, or microbial cultures, may be used as both reducing and stabilizing agents. The topic of energy efficiency takes center stage here; typical nanomaterial synthesis can involve high-temperature heating over long periods, whereas green nanotechnology methods include microwave, photochemical, or biosynthesis, all in ambient conditions that consume less energy. Safer solvents are selected as alternatives to volatile organic compounds, resulting in environments with lower toxicity and environmental effects through water, ethanol, and supercritical carbon dioxide. And, lastly, safety and sustainability will rely on the design of actual nanomaterials to ensure that the overall products being developed are not only effective for the envisioned sensing type in the application, but also do not cause undue long-term ecological damage ^[17,18].

2.2. Eco-Friendly Synthesis Routes

The difference between green nanotechnology and conventional nanomaterial production is most conspicuous in the selection of synthesis methods. Biological synthesis is also known as biogenic synthesis, whereby natural reducing and capping agents are used, such as in plants, microorganisms, or enzymes. Nanoparticles can be synthesized quickly at ambient temperature and using plant materials to reduce metal salts and concurrently stabilize the formed nanostructures. The principle of microbial synthesis is the ability of live organisms of bacteria, fungi, or algae to respond to intrinsic metabolic demands, causing them to reduce dissolved metal ions into nanoparticles of distinctive shapes and surface chemistries. Enzyme-mediated synthesis offers another variation, enabling highly selective and mild production of nanomaterials with precise size control. Alongside these biological routes, there are green physical and chemical approaches, such as microwave-assisted synthesis, which achieves rapid and uniform heating; solvent-free mechanochemical synthesis, which eliminates the use of harmful solvents altogether; and supercritical fluid synthesis, which utilizes environmentally benign supercritical carbon dioxide as both a reaction medium and a solvent. Hydrothermal and solvothermal methods using green solvents like water or ethanol can produce high-quality nanomaterials without generating toxic byproducts. Many of these eco-friendly methods impart the nanoparticles with surface functionalities originating from the biological agents or solvents themselves, which can be advantageous in environmental sensing applications because they provide natural binding sites for pollutants. An overview of the major physical, chemical, and biological synthesis methods, categorized under top-down and bottom-up approaches, is illustrated in **Figure 1**. The schematic highlights how green nanotechnology emphasizes environmentally benign routes, particularly biological and low-energy chemical methods, which align with sustainable applications in environmental sensing and monitoring ^[2,19,20].

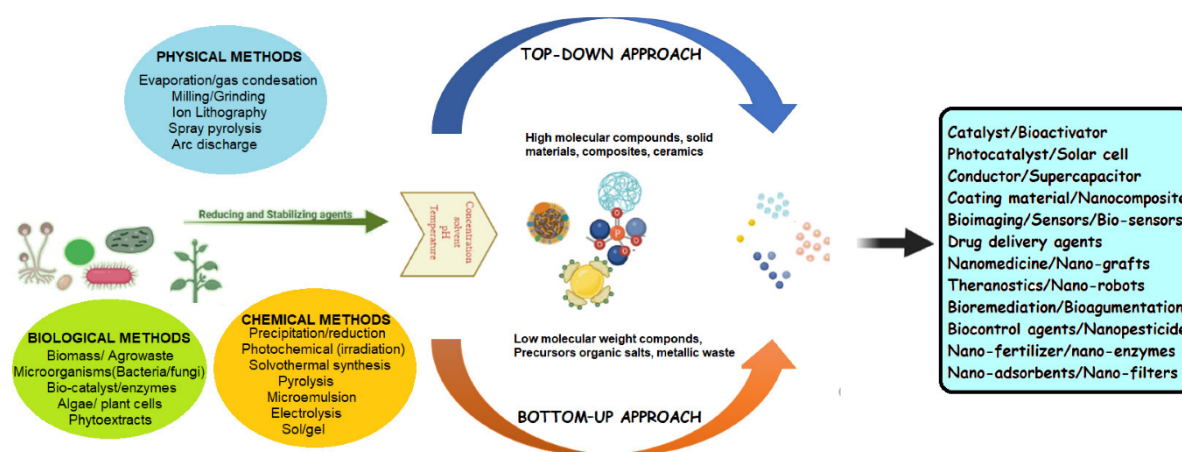


Figure 1. Schematic representation of the synthesis of nanoparticles by top-down and bottom-up approaches and their applications ^[20].

2.3. Life Cycle Thinking and Assessment

A defining characteristic of green nanotechnology is its emphasis on life cycle thinking. The sustainability of a nanomaterial cannot be judged solely by its method of synthesis but must account for its entire journey, from the sourcing of raw materials through production, deployment, and eventual disposal. Life cycle assessment, or LCA, provides a structured way to quantify the environmental footprint at each stage. At the raw material stage, this involves considering whether the precursors are derived from finite, energy-intensive sources or from renewable, low-impact alternatives. During synthesis and manufacturing, LCA examines energy use, greenhouse gas emissions, and waste generation. In the deployment phase, it considers whether the sensor materials might leach nanoparticles into the environment and whether those particles degrade safely. At

the end-of-life stage, it evaluates whether the materials can be recycled, biodegraded, or otherwise disposed of without persisting as pollutants. LCA thus allows direct comparison between conventionally produced and green-synthesized nanomaterials, revealing not only the environmental benefits but also trade-offs that might arise in scaling up green approaches ^[21,22].

2.4. Comparing Conventional and Green Approaches

The core differences between conventional and green nanotechnology in environmental sensing are summarized in **Table 1**. This comparison highlights how environmentally responsible synthesis can simultaneously enhance material safety, reduce production impacts, and sometimes improve sensor performance ^[2,23–25].

Table 1. Comparison between conventional nanotechnology and green nanotechnology in environmental sensing applications.

Aspect	Conventional Nanotechnology	Green Nanotechnology
Reducing Agents	Toxic chemicals (e.g., hydrazine, sodium borohydride)	Plant-derived polyphenols, enzymes, microbial metabolites
Solvents	Volatile, toxic organics (e.g., toluene, chloroform)	Water, ethanol, supercritical CO ₂
Energy Requirements	High-temperature, long-duration heating	Ambient conditions, microwave, photochemical, or enzymatic methods
Waste Generation	Significant hazardous byproducts	Minimal, often biodegradable waste
Surface Functionalization	Requires post-synthesis modification	Often intrinsic from biological capping agents
Toxicity Profile	Potentially high ecotoxicity	Reduced toxicity, improved biocompatibility
Feedstock Source	Non-renewable, petrochemical-based	Renewable biomass, agricultural waste

2.5. Relevance to Environmental Sensing

In environmental sensing, these principles translate into tangible performance benefits. The organic compounds from plant extracts or microbial systems that cap green-synthesized nanoparticles introduce reactive functional groups that can enhance sensitivity and selectivity toward specific pollutants. The biocompatibility of these materials means that sensors can be deployed directly in sensitive environments such as rivers, wetlands, or agricultural soils without introducing new contaminants. Cost advantages also emerge when renewable or waste-derived feedstocks are used, enabling wider deployment of sensing networks in resource-limited contexts. Furthermore, green-synthesized nanomaterials can be integrated into biodegradable or recyclable sensing platforms, ensuring that the monitoring systems themselves do not add to the environmental burden they are intended to mitigate. In this way, green nanotechnology offers not only a pathway to more responsible material production but also a means to develop environmental sensing technologies that embody the very sustainability they aim to safeguard ^[26].

3. Nanomaterials for Environmental Sensing

Nanomaterials form the structural and functional backbone of modern environmental sensing technologies. Their exceptional properties—such as high specific surface area, tunable surface chemistry, quantum effects at small scales, and superior catalytic activity—enable the detection of pollutants at extremely low concentrations. The unique interactions that occur at the nanoscale amplify sensor responses, making it possible to identify trace amounts of contaminants in complex environmental matrices such as wastewater, atmospheric aerosols, or agricultural soils. In green nanotechnology, the emphasis is not only on the performance of these nanomaterials but also on their method of production, ensuring that they are derived from renewable sources, synthesized through eco-friendly processes, and designed to be safe for long-term environmental exposure. The performance of nanomaterials in environmental sensing is governed by their intrinsic physicochemical properties ^[27,28]. As summarized in **Figure 2**, carbon-based, metal-based, and metal oxide nanomaterials exhibit distinct advantages—such as high electrical conductivity, catalytic

activity, and efficient charge separation—that enable sensitive and selective pollutant detection. These properties are further enhanced when nanomaterials are synthesized via green routes, which often impart additional biocompatibility and sustainability benefits.

3.1. Types of Green-Synthesized Nanomaterials

Several categories of nanomaterials are particularly relevant for environmental sensing applications, each offering distinctive advantages and functionalities. Metal nanoparticles, such as gold, silver, and copper, are valued for their surface plasmon resonance properties, which enhance optical sensing techniques, and for their catalytic capabilities in chemical detection. When synthesized using plant extracts, microbial cultures, or enzyme-assisted methods, these metals not only retain their high sensitivity but also gain improved environmental compatibility. Metal oxide nanomaterials, including zinc oxide (ZnO), titanium dioxide (TiO₂), and iron oxides, are widely used in electrochemical and photocatalytic sensing due to their semiconducting nature, high stability, and ability to interact selectively with gases and aqueous pollutants. These oxides are frequently synthesized using green synthetic techniques that yield oxide materials with characteristic morphologies, such as nanorods, nanosheets, or porous structures, which can further improve sensing capability ^[29].

The nanomaterials based on carbon, especially graphene and carbon nanotube (CNT)/carbon quantum dots, have a unique place in the world of sensing due to their excellent electric conductivity, huge surface area, as well as the possibility of diverse functionalization. When made out of biomass pre-products, such as coconut shells, farm waste, or food waste, they are sustainable as well as high-performance sensors. One example is the preparation of carbon quantum dots through the hydrothermal synthesis of fruit peels or sugar solutions, yielding photoluminescence nanoparticles that can be used as sensitive detection probes for target heavy metals or organic pollutants. Given their tunable structures and outstanding physicochemical characteristics, the sensitivity and selectivity of carbon-based nanomaterials make them exceptionally versatile in environmental sensing. This class comprises Tolson (2009) graphene derivatives (e.g., graphene oxide,

reduced graphene oxide), carbon nanotubes, and quantum dots, which all have characteristic strengths in terms of surface area, conductivity, and functionalization potential, as shown in **Figure 3**. These materials are increasingly synthesized through green routes—such as biomass-derived precursors—to enhance their sustainability while

maintaining performance. Polymer-based nanomaterials, both synthetic and natural, are also used in sensing applications, particularly when biopolymers such as chitosan or cellulose nanofibers are incorporated. These materials offer inherent biocompatibility and can act as both sensing substrates and functional binding layers^[30].

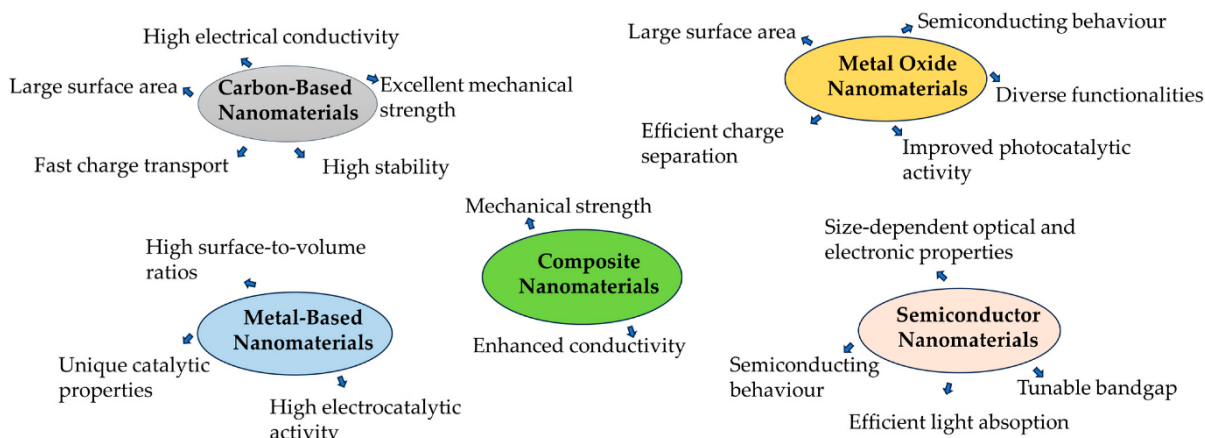


Figure 2. Properties of some nanomaterials.

Carbon-Based Nanomaterials

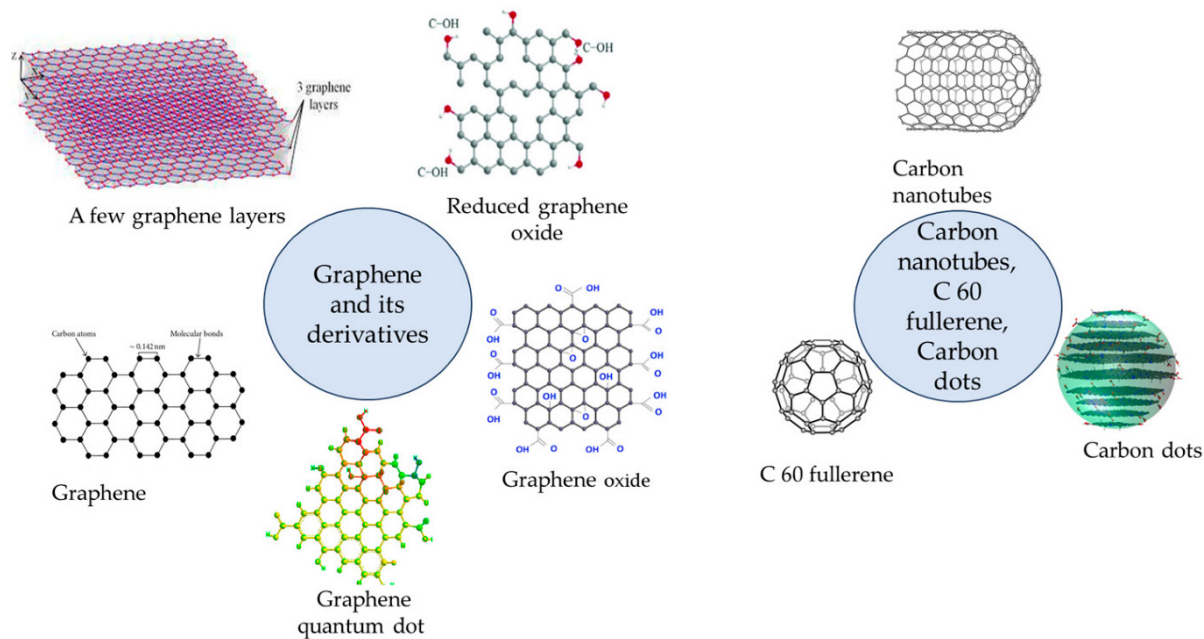


Figure 3. Graphene and its derivatives, carbon nanotubes, C60 fullerene, and carbon dots.

3.2. Structure–Property–Performance Relationship

The effectiveness of a nanomaterial in environ-

mental sensing is determined by the interplay between its structural characteristics and the properties they confer. For instance, nanoparticles with high aspect ratios, such as nanorods or nanotubes, provide more active sites for

analyte interaction compared to spherical particles of the same mass. The porosity and roughness of the surfaces have an effect on adsorption kinetics, which translates into sensor response time and detection limit. Selectivity and sensitivity are further modified through crystal structure, density of defects, and functional groups. These structural parameters may be affected favorably by green synthesis. As an example, the functionalization of nanoparticles, which can lead to improved dispersion and affinity for a given contaminant in aqueous mediums, can occur when the nanoparticles are coated with organic functional groups via a plant-mediated reduction process. Equally, the metal oxides produced within the body can have a high defect density value and therefore be responsive to shifts in environmental conditions ^[27].

3.3. Advantages of Green-Synthesized Nanomaterials for Sensing

Green nanotechnology presents a number of unique benefits to environmental sensor design. The existence of natural capping agents in biological synthesis, in addition to stabilizing the nanoparticle, provides chemical groups

(e.g., hydroxyl, carboxyl, and amine) that act as specific attachment sites for analytes. The lower toxicity and improved biodegradability of these materials allow for their safe use in field-deployed sensors, particularly in ecosystems where the introduction of harmful materials would be counterproductive. Furthermore, the cost-effectiveness of using renewable feedstocks and low-energy synthesis methods supports the scalability of sensor networks for widespread monitoring programs. The integration of green-synthesized nanomaterials into sensing platforms aligns with the growing demand for technologies that are both high-performing and environmentally responsible ^[31].

3.4. Representative Examples and Applications

Table 2 summarizes key categories of green-synthesized nanomaterials used in environmental sensing, their common synthesis methods, and representative applications. This table demonstrates the diversity of materials available and how their eco-friendly synthesis routes can be tailored to specific environmental monitoring needs.

Table 2. Examples of green-synthesized nanomaterials for environmental sensing and their applications.

Nanomaterial Type	Common Green Synthesis Method	Target Analytes in Environmental Sensing	Representative Application Example
Gold nanoparticles	Plant extract-mediated reduction	Heavy metals (Hg ²⁺ , Pb ²⁺), pesticides	Optical colorimetric sensors for mercury detection in water
Silver nanoparticles	Microbial reduction (fungi, bacteria)	Pathogens, nitrates, chlorinated compounds	Antimicrobial water quality monitoring systems
Zinc oxide nanorods	Hydrothermal synthesis using plant extracts	Volatile organic compounds, ammonia	Gas sensors for indoor and outdoor air quality assessment
Carbon quantum dots	Hydrothermal conversion of biomass waste	Pb ²⁺ , Fe ³⁺ , organic dyes	Fluorescent probes for heavy metal detection in wastewater
Graphene oxide	Green oxidation of biomass-derived graphite	VOCs, NO ₂ , SO ₂	Chemiresistive gas sensors for industrial emission monitoring
Chitosan-based nanofibers	Electrospinning with natural polymer sources	Pesticides, herbicides	Disposable biosensors for agricultural soil analysis

3.5. Implications for Sensor Design

Environmental sensors are chosen based on nanomaterial, which determines the detection mechanism, the stability of the sensor operation, its sensitivity, and environmental sustainability. By uniting green-synthesized nanomaterials with the design of the sensors, one can not only preserve or even improve the analytical perfor-

mance of the sensor but also sustain the material until the end of its lifetime. This combination of functional and eco-fit attributes places green nanotechnology in a leading role to provide the next generation of environmental monitoring systems. With the mounting problems of the surrounding environment, such materials provide a way towards both environment-friendly and change-sensitive sensors ^[32].

4. Sensing Mechanisms and Technologies

The functionality of the environmental sensor is contingent upon both the nanomaterials used in the sensor and the sensing mechanism by which it identifies the target analytes. Sensing mechanisms deliver, as a readable signal—usually optical, electrical, or mechanical—the interaction between a contaminant and the nanomaterial making it interpretable as processed by the sensing mechanism. The selection of the mechanism and issues concerning the nature of the analyte, the physical and chemical properties of the sensing material, the intended detection limit, and the environmental conditions in which the sensor is intended to operate are all relevant in determining the choice of mechanism. Green nanotechnology introduces a second set of variables into this selection process, as the sustainability and safety of the sensing platform must be weighed against the high sensitivity, selectivity, and stability required^[33].

4.1. Optical Sensing

Optical sensing mechanisms rely on the interaction between light and nanomaterials to produce detectable changes in color, fluorescence, absorbance, or refractive index. In colorimetric sensing, for instance, the aggregation or dispersion of metallic nanoparticles, such as green-synthesized gold or silver nanoparticles, changes their localized surface plasmon resonance (LSPR) properties, leading to visible color shifts that can be detected with the naked eye or simple optical devices. Fluorescent sensing, on the other hand, exploits the emission of light by photoluminescent nanomaterials such as carbon quantum dots or doped semiconductor nanoparticles. These materials, when produced via eco-friendly routes, often carry surface groups that enhance selective binding to specific analytes, thereby improving the accuracy of fluorescence-based detection. Surface plasmon resonance (SPR) sensing uses the resonance of conduction electrons on a metal surface to detect minute changes in refractive index caused by analyte adsorption, offering label-free and real-time monitoring^[34].

4.2. Electrochemical Sensing

Electrochemical sensing mechanisms convert chem-

ical interactions into measurable electrical signals, such as current, voltage, or impedance changes. In amperometric and voltammetric sensors, the target analyte undergoes a redox reaction at the surface of the electrode, producing a current proportional to its concentration. Green-synthesized nanomaterials, such as biosynthesized zinc oxide or plant-derived graphene, serve as active electrode modifiers, enhancing electron transfer and increasing surface area for interaction. Impedance-based sensing measures the resistance and capacitance changes at the electrode-electrolyte interface upon analyte binding, allowing for highly sensitive and label-free detection. Electrochemical methods are particularly suitable for detecting heavy metals, pesticides, and organic pollutants in water and soil, as they offer high sensitivity, portability, and low cost^[35].

4.3. Mass-Based and Piezoelectric Sensing

Mass-based sensing mechanisms detect the minute changes in mass that occur when analytes bind to a sensing surface. Quartz crystal microbalance (QCM) sensors, for example, operate on the principle that the resonance frequency of a quartz crystal changes in proportion to the mass added to its surface. When coated with green-synthesized nanomaterials such as biopolymer-functionalized nanoparticles or biosynthesized metal oxides, these sensors gain selectivity toward specific contaminants while remaining environmentally safe for deployment. Surface acoustic wave (SAW) devices function in a similar way but detect shifts in acoustic wave propagation due to mass or viscoelastic changes at the surface. These systems are valuable for real-time, label-free detection of pollutants in both gaseous and liquid environments^[36].

4.4. Integration with IoT and Wireless Monitoring

The future of environmental sensing lies in interconnected, real-time monitoring systems that can operate autonomously in the field. Green-synthesized nanomaterials are increasingly being integrated into miniaturized, low-power sensors that connect to wireless networks and the Internet of Things (IoT). This integration allows for continuous data collection from distributed sensing nodes, enabling real-time analysis of environmental trends. The

use of eco-friendly materials in such systems ensures that large-scale deployment does not contribute to environmental degradation. In addition, biodegradable sensor platforms are being explored for temporary monitoring in sensitive ecosystems, where they can safely degrade after their functional life.

4.5. Representative Sensing Mechanisms and Applications

Table 3 summarizes the major sensing mechanisms used in environmental monitoring, their working principles, the types of green-synthesized nanomaterials typically used, and representative applications.

Table 3. Sensing mechanisms, principles, and applications using green-synthesized nanomaterials.

Sensing Mechanism	Working Principle	Typical Green-Synthesized Nanomaterials	Representative Application Example
Colorimetric	Aggregation/dispersal changes nanoparticle LSPR, producing visible color shift	Gold nanoparticles from plant extracts	Detection of mercury ions in river water
Fluorescent	Light emission from photoluminescent nanomaterials changes upon analyte binding	Carbon quantum dots from fruit peel waste	Sensing of lead ions in wastewater
Surface Plasmon Resonance	Refractive index change alters resonance conditions of surface plasmons	Green-synthesized silver thin films	Monitoring pesticide residues in agricultural runoff
Amperometric/Voltammetric	Redox reaction generates measurable current proportional to analyte concentration	Biosynthesized zinc oxide nanoparticles	Detection of nitrates in groundwater
Impedance-based	Analyte binding alters resistance/capacitance at electrode interface	Graphene from biomass-derived precursors	Detection of volatile organic compounds in air
Quartz Crystal Microbalance	Resonance frequency shifts with added mass on sensor surface	Chitosan-coated biosynthesized gold nanoparticles	Real-time detection of bacterial contamination in drinking water
Surface Acoustic Wave	Acoustic wave propagation changes with mass or viscoelastic property variations	Green-synthesized TiO ₂ nanostructures	Gas sensing of ammonia in industrial emissions

4.6. Implications for Environmental Monitoring

The choice of sensing mechanism in an environmental monitoring system has implications for sensitivity, selectivity, portability, and long-term reliability. Optical systems often offer simple and rapid detection, electrochemical systems provide high sensitivity in compact devices, and mass-based systems excel in real-time, label-free operation. Green nanotechnology enhances each of these mechanisms by supplying nanomaterials that are not only effective in signal generation but also safe for the environment. This dual advantage ensures that as sensing networks expand and become more integrated with digital infrastructure, they will do so in a way that aligns with the principles of environmental stewardship.

5. Applications in Environmental Monitoring

The infiltration of green-synthesized nanomaterials into environmental sensing platforms has provided small opportunities to monitor and trace pollutants in aquatic

environments, the atmosphere, soil, and climate systems. These applications extend beyond laboratory demonstrations to real-world monitoring, where sustainability, safety, and long-term performance are at least as important as sensitivity and detection limits. A synthesis of the high-performance nanomaterials and the eco-friendly synthesis methods has enabled the development of sensors that are effective in field applications and decreases the ecological impact. Green nanotechnology can be used to identify virtually any kind of pollutant, except for heavy metals and organic chemicals, making it an essential component of current environmental protection policies. Green nanotechnology is of great importance in addressing environmental pollution, whereby toxic pollutants are transformed into nontoxic substances through sound environmental practices. Biogenic nanomaterials (based on agro-waste, microbial cells, or enzymes) facilitate specific pollutant removal (e.g., dyes, pesticides, or endocrine disruptors) through nano-sorbents, nanocomposites, and nanofillers, as shown in **Figure 4**. These developments not only minimize pollutants within soil, water, and air, but they also enhance restoration of the ecosystems and enrichment of the ecosystems^[37].

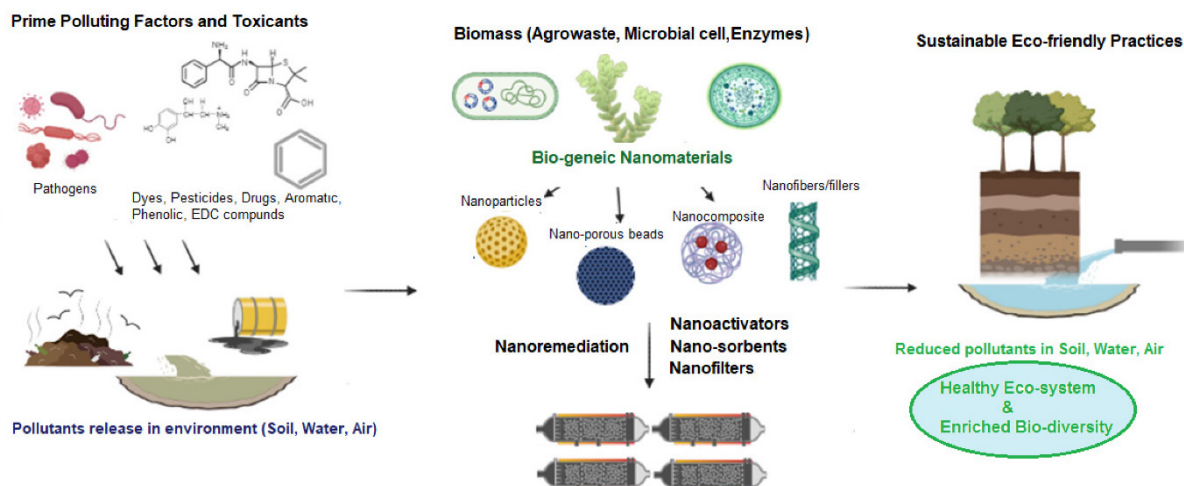


Figure 4. Role of green nanotechnology in bioremediation and environmental pollution control [20].

5.1. Water Quality Monitoring

Water systems are among the most vulnerable to contamination from industrial effluents, agricultural runoff, and domestic waste. Green-synthesized nanomaterials have been widely deployed for the detection of heavy metals such as lead, mercury, and arsenic, which are toxic even at trace levels. For example, gold nanoparticles synthesized using plant extracts have been used in colorimetric sensors that provide a visible color change upon binding to mercury ions, enabling simple, on-site testing without the need for complex instrumentation. Similarly, biosynthesized zinc oxide nanostructures have been incorporated into electrochemical sensors for detecting nitrates and phosphates, which are key contributors to eutrophication in aquatic ecosystems. In microbial contamination detection, silver nanoparticles produced through fungal synthesis have shown high antimicrobial activity, enabling their use in rapid pathogen detection kits for drinking water safety [38].

5.2. Air Quality Sensing

In redux, air pollution poses grave threats to human health and the environment. Pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO₂), volatile organic compounds (VOCs), and particulate matter are known to cause respiratory ailments, global warming, and environmental degradation. Titanium dioxide and zinc oxide are

green-synthesized metal oxides that have been prepared to form a gas sensor capable of detecting VOCs and ammonia at part-per-billion concentrations. Sensors of Chemi resistive type have been implemented using carbon-based nanomaterials obtained as waste of biomass including graphene oxide and carbon nanotubes to protect against industrial emissions and air pollution in the city. Such sensors are not only sensitive and have a quick response time, but they can be constantly monitored once put in Internet of Things (IoT) networks, which can give real-time reporting of trends in air quality [39].

5.3. Soil Contamination Detection

Soil contamination by heavy metals, agrochemicals, and hydrocarbons can severely impact agricultural productivity and food safety. Green-synthesized nanomaterials are increasingly being employed in portable soil testing devices, enabling farmers and environmental agencies to monitor contamination on-site. Chitosan-based nanocomposites, produced through green processing methods, have been used as biosensors for detecting pesticide residues in agricultural soils. Similarly, plant-mediated silver nanoparticles have been incorporated into electrochemical platforms for detecting polycyclic aromatic hydrocarbons (PAHs) in soils near industrial sites. The biodegradable nature of many green nanomaterial-based sensing platforms allows for their safe disposal after use, minimizing secondary pollution risks.

5.4. Climate-Related Monitoring

Green nanotechnology is also making contributions to climate-related environmental monitoring. Sensors incorporating green-synthesized nanomaterials have been developed to measure greenhouse gases such as carbon dioxide, methane, and nitrous oxide with high sensitivity. For example, surface acoustic wave sensors coated with biosynthesized titanium dioxide have been used for ammonia detection in livestock farming facilities, where ammonia emissions contribute indirectly to greenhouse gas production. Optical sensors utilizing green-derived graphene

have been applied for detecting changes in atmospheric composition related to urban heat island effects and industrial emissions, providing valuable data for climate modeling and policy development^[40,41].

5.5. Representative Applications Across Environmental Compartments

Table 4 summarizes representative applications of green-synthesized nanomaterials in environmental monitoring, highlighting the target analytes, nanomaterials used, and sensing techniques involved.

Table 4. Applications of green-synthesized nanomaterials in environmental monitoring.

Environmental Medium	Target Analyte(s)	Green-Synthesized Nanomaterial	Sensing Technique	Representative Example
Water	Hg ²⁺ , Pb ²⁺ , As ³⁺	Gold nanoparticles from plant extracts	Colorimetric	Detection of mercury in river water
Water	Nitrates, phosphates	Biosynthesized zinc oxide nanorods	Electrochemical (amperometric)	Monitoring agricultural runoff
Water	E. coli, pathogens	Fungal-synthesized silver nanoparticles	Optical (plasmonic)	Rapid microbial contamination detection
Air	VOCs, ammonia	Green-synthesized ZnO nanostructures	Chemiresistive gas sensing	Indoor air quality monitoring
Air	NO ₂ , SO ₂	Biomass-derived graphene oxide	Electrochemical (impedance)	Industrial emission monitoring
Soil	Pesticides	Chitosan-based nanocomposites	Biosensing (enzyme-linked)	On-site agricultural soil analysis
Soil	PAHs	Plant-mediated silver nanoparticles	Electrochemical	Soil contamination monitoring near industrial areas
Climate	Ammonia, CO ₂	Biosynthesized TiO ₂ thin films	Surface acoustic wave sensing	Emission tracking in livestock farms

5.6. Broader Impact on Environmental Management

The practical deployment of these sensing technologies is transforming environmental monitoring from a reactive process into a proactive one. Instead of waiting for contamination to reach critical levels before taking action, green nanotechnology-based sensors allow for early detection and rapid intervention. This proactive monitoring approach is particularly valuable for compliance with environmental regulations, public health protection, and the preservation of biodiversity. The sustainability aspect ensures that the monitoring process itself does not add to the environmental burden, setting a precedent for future technological innovations in environmental management^[14,42,43].

6. Challenges and Future Perspectives

Although green nanotechnology is a promising alternative for sustainable and high-performance environmental sensing, many challenges should be tackled for it to be broadly adopted. The challenges are technical, environmental, economic, and regulatory, and will be addressed through the coordinated efforts of members from the research and industry communities, as well as the policy-making community. The key to effective green nanotechnology application in environmental sensing will be to balance performance and sustainability, ensuring that innovations meeting current environmental monitoring demands do not compromise ecological balance.

6.1. Technical Challenges

Reproducibility is one of the most longstanding problems in the domain. Biological systems-based Green approaches generally involve natural product extracts or microbial cultures, the composition of which can vary with growth conditions, season, or geographic source. This has the potential to cause inconsistency in the measured nanoparticle size, shape, and surface chemistry, which will eventually influence the performance and reliability of sensors. Another big issue is scalability, as most green synthesis pathways are efficient at the lab scale, scaling them up to an industrial scale without losing pronounced environmental benefits is a multifaceted engineering problem. Moreover, there is a significant technical challenge in incorporating green-synthesized nanomaterials into sound sensor platforms that can operate for extended periods to address real-world conditions including but not limited to recurrent temperature changes, humidity, and contaminant concentrations.

6.2. Environmental and Health Safety Concerns

The long-term behaviour of green nanomaterials in the environment and their possible bioaccumulation capabilities are still unclear, although one would expect a lesser toxic effect compared to the conventionally synthesized equivalents of the former. Nanoparticles can also have deleterious effects when produced by biological processes that are maintained in ecosystems or disrupt microbial communities. Extensive nanotoxicology research with both acute and chronic exposure is required to test their safety in various environmental compartments. Standardized test procedures are also needed, which can be used universally so that the risk assessment of a study is comparable to another study.

6.3. Economic and Policy Considerations

Economically, green nanotechnology has to prove competitive with the already established mass production methods. Although renewable feed and low-energy pro-

cesses can make a lot of savings in the long run, they may require a heavy investment in the initial green production infrastructure. Policy structures are also an important factor in this: subsidies, tax credits, or regulatory credits on sustainable manufacturing would promote the growth of such motivation. On the other hand, the lack of transparent rules on green nanomaterials is likely to impair commercialization due to uncertainty about what is required. International agencies and governments will be required to come up with laws that facilitate innovation as well as environmental and health safety.

6.4. Emerging Trends and Research Directions

Green nanotechnology in environmental sensing would probably follow a number of emerging trends. The new generation of green-synthesized nanoparticles, hybrid nanomaterials (composites of green-synthesized nanoparticles and other sustainable materials, including biodegradable polymers or biochar), is attracting increased interest due to their functional multiplicity in sensing applications. Autonomous sensors, Self-powered sensors that tap ambient power sources such as light, heat, or mechanical vibrations, will be developed to limit the need to funnel energy in other power sources and to increase deployment time. Data analysis is also a gateway with the advent of artificial intelligence and machine learning advances that would allow sensors to recognize complex patterns in pollutants to anticipate environmental trends. Moreover, biodegradable sensor platforms can be used as a convenient temporary monitoring solution in sensitive locations, such as wetlands or conservation areas, where traditional devices can be disruptive.

6.5. Summary of Challenges and Opportunities

Table 5 presents a concise overview of the key challenges currently facing green nanotechnology in environmental sensing and the potential strategies to address them.

Table 5. Challenges and potential solutions for advancing green nanotechnology in environmental sensing.

Challenge Category	Specific Issue	Potential Solution
Technical	Variability in biological synthesis routes	Standardize precursor preparation; use controlled cultivation and extraction methods
Technical	Limited scalability of green synthesis	Develop continuous-flow and modular green production systems
Environmental/Safety	Uncertain long-term ecological impacts	Conduct comprehensive life cycle and nanotoxicology studies
Environmental/Safety	Lack of standardized safety testing protocols	Establish international guidelines for green nanomaterial risk assessment
Economic/Policy	Higher initial production costs	Provide subsidies, tax incentives, and regulatory credits for sustainable manufacturing
Economic/Policy	Lack of clear regulatory framework	Develop specific standards for green nanotechnology in environmental applications
Innovation/Research	Need for multifunctional, durable sensor platforms	Explore hybrid nanomaterials and bio-integrated sensing systems
Innovation/Research	Power requirements for remote monitoring	Develop self-powered, energy-harvesting sensing devices

6.6. Outlook

Looking forward, the field is poised for rapid growth if these challenges can be addressed through interdisciplinary collaboration. Chemists, materials scientists, environmental engineers, toxicologists, and policymakers will need to work in concert to refine synthesis methods, evaluate safety comprehensively, and create supportive economic and regulatory environments. The ultimate goal is to establish green nanotechnology as a mainstream approach in environmental monitoring—one that delivers high sensitivity and selectivity while embodying the principles of sustainability at every stage of its life cycle. Achieving this vision will not only improve our ability to protect the environment but will also set a precedent for how advanced technologies can be developed responsibly.

7. Conclusions

Green nanotechnology has emerged as a transformative approach to environmental sensing and monitoring, bridging the gap between high-performance analytical capabilities and the imperative for ecological responsibility. Aligning the synthesis, functionalization, and deployment of nanomaterials with the principles of green chemistry offers a pathway toward sensor systems that are both technologically advanced and environmentally benign. This review has traced the evolution of the field from its foundational principles through the types of green-synthesized

nanomaterials available, the sensing mechanisms they enable, their diverse applications across environmental compartments, and the challenges that remain in their large-scale adoption.

The discussion has shown that green-synthesized nanomaterials—whether metallic, metal oxide, carbon-based, or polymeric—can be produced through eco-friendly routes such as plant-mediated reduction, microbial synthesis, or low-energy chemical and physical processes. These methods not only eliminate or reduce the use of hazardous chemicals but also frequently impart beneficial structural and surface characteristics that enhance sensor performance. When incorporated into optical, electrochemical, mass-based, or hybrid sensing platforms, these materials enable the detection of contaminants at trace levels in water, air, soil, and atmospheric systems, contributing to more accurate, timely, and sustainable environmental monitoring.

The integration of such materials into practical sensing devices demonstrates that environmental stewardship and technological innovation need not be mutually exclusive. Whether identifying the presence of heavy metals in river water or tracking greenhouse gas emissions in crop fields, the applications discussed in this review demonstrate how green nanotechnology is transforming our ability to observe and respond to environmental changes. The implementation of these devices in Internet of Things (IoT) networks and wireless surveillance systems further increases their useful-

ness, enabling real-time distributed information gathering and analysis on a scale not previously accomplished.

Not everything is smooth during this road to mainstream adoption, however. Sustained academic interdisciplinary collaboration is necessary to resolve technical issues concerning reproducibility, scalability, and environmental issues, such as long-term and biodegradability of nanomaterials, as well as economic and regulatory uncertainties. The success of the underlying premise that these technologies can be scaled responsibly will depend on life cycle assessments, well-established safety processes, and accessible policy frameworks. Meanwhile, new research area, including the creation of hybrid nanomaterials, self-powered sensors, biodegradable platforms, and the use of AI-aided data analysis, presents exciting opportunities to move beyond existing shortcomings and scale up ability.

Finally, green nanotechnology for sensing and monitoring the environment is one of the new scientific and moral frontiers. It reflects the concept that innovation must not only address the problem, at hand but also prevent its self-destruction. Adhering to this philosophy, the scientific world can develop sensing routines that eclipse mere detection of a threat to the environment, serving, in fact, as a model of future sustainability, to which they are properties. Now the challenge is shifting these ideas out of the laboratories to world-deployed systems, as the idea that we pinpoint our planet more closely than ever, we are also taking care of it more intelligently.

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