

Green-Synthesized Nanomaterials for Sustainable Sensor Development: Principles, Characterization, Sensing Mechanisms, and Applications-A Comprehensive Review

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Abstract: Green chemistry has become an important framework for developing materials and technologies that reduce the use of hazardous substances, minimize waste, improve energy efficiency, and make greater use of renewable resources. Its integration with nanotechnology has created new opportunities for the preparation of nanomaterials through biologically mediated and environmentally considerate approaches. In particular, plants, microorganisms, algae, biomolecules, and renewable biomass can provide naturally occurring compounds that participate in the reduction, nucleation, growth, capping, and stabilization of nanoparticles. Phytochemicals such as polyphenols, flavonoids, alkaloids, terpenoids, proteins, sugars, amino acids, and organic acids may therefore perform functions that would otherwise require synthetic reducing or stabilizing agents. The resulting nanomaterials can display distinctive optical, catalytic, electronic, magnetic, and surface properties that are valuable for sensing.

This review presents an expanded discussion of green nanomaterial synthesis and its integration with modern sensing technologies. Plant-mediated, microbial, and algae-mediated synthesis routes are considered, followed by an overview of major green-synthesized nanomaterials, including silver, gold, zinc oxide, iron oxide, copper and copper oxide, and carbon-based nanomaterials. The importance of physicochemical characterization is discussed using ultraviolet-visible spectroscopy, Fourier-transform infrared spectroscopy, X-ray diffraction, transmission electron microscopy, scanning electron microscopy, dynamic light scattering, zeta-potential analysis, and elemental or surface analysis. The review further examines electrochemical, optical, colorimetric, fluorescence, and biosensor platforms and explains how nanomaterials can improve analyte interaction, electron transfer, catalytic activity, optical response, and signal amplification.

Applications in environmental monitoring, healthcare diagnostics, food safety, agriculture, and portable analytical systems are described. Although green synthesis offers important advantages, the use of a biological material alone does not automatically establish environmental sustainability or biological safety. Reproducibility, scalability, extract composition, nanoparticle stability, toxicity, standardization, real-sample validation, waste generation, energy consumption, and complete life-cycle impacts must also be considered. Future development is expected to involve standardized green synthesis, sustainable-by-design nanomaterials, smartphone-assisted sensing, microfluidics, artificial intelligence and machine learning, multiplexed detection, and connected portable platforms. The convergence of green chemistry, nanotechnology, and sensing therefore offers a promising pathway toward sensitive, selective, affordable, portable, and environmentally responsible analytical systems.

Keywords: Green chemistry; Green synthesis; Nanomaterials; Nanoparticles; Biosensors; Electrochemical sensors; Optical sensors; Colourimetric sensors; Phytochemicals; Sustainable nanotechnology; Environmental monitoring; Biomarkers; Nanobiosensing.

1. INTRODUCTION

The rapid development of nanotechnology has expanded the use of nanoscale materials across healthcare, environmental science, agriculture, food technology, energy, and industrial processes. Nanomaterials differ substantially from their bulk counterparts because their nanoscale dimensions produce high surface-to-volume ratios, increased surface reactivity, size-dependent optical and electronic behavior, and tunable physicochemical characteristics. These properties are particularly important in sensing, where the interaction between a nanostructured surface and a target analyte determines how efficiently a measurable signal can be generated [27].

Despite these advantages, many conventional nanoparticle synthesis procedures depend on strong reducing agents, organic solvents, elevated temperatures, high pressures, or energy-intensive processing. Such conditions can increase the environmental burden of production, generate unwanted by-products, and create additional requirements for purification and waste treatment. Consequently, the development of safer and more sustainable synthesis strategies has become an important objective in nanoscience [3].

Green chemistry provides a systematic framework for addressing these concerns. Rather than focusing only on the final product, green chemistry considers the materials, solvents, energy requirements, reaction efficiency, waste generation, safety, and environmental consequences associated with a process. When these principles are applied to nanotechnology, the resulting field is often described as greener or sustainable nanotechnology. The objective is not merely to replace a synthetic chemical with a plant extract, but to improve the overall material and process profile [1].

Among biological synthesis strategies, plant-mediated synthesis has received extensive attention because plants contain diverse metabolites capable of participating in nanoparticle formation. Different plant parts, including leaves, stems, roots, bark, flowers, fruits, seeds, and peels, may serve as sources of functional molecules. These compounds can contribute to reduction of metal ions and subsequent stabilization of the newly formed particles. Similar concepts have been explored using bacteria, fungi, yeast, algae, and other biological resources [29].

The integration of green-synthesized nanomaterials with sensor technology is particularly significant. Nanomaterials can provide a large active surface for analyte binding, facilitate electron transfer, enhance catalytic reactions, modify optical signals, and provide functional groups for immobilizing recognition molecules. These features can support sensors capable of detecting heavy metals, pesticides, pathogens, toxins, organic pollutants, food contaminants, and clinically relevant biomarkers [9, 24].

The objective of this review is to provide a comprehensive and clearly organized account of green-synthesized nanomaterials and their role in modern sensing systems. The review covers the principles of green chemistry, biological synthesis mechanisms, major classes of green nanomaterials, characterization methods, sensing mechanisms, sensor platforms, application areas, advantages, challenges, and future research directions.

2. GREEN CHEMISTRY AS A FOUNDATION FOR SUSTAINABLE NANOTECHNOLOGY

Green chemistry aims to reduce or eliminate the use and generation of hazardous substances throughout the life cycle of a chemical process. In nanomaterial synthesis, this concept becomes particularly important because nanoparticle production may involve multiple stages, including precursor preparation, reduction or precipitation, nucleation, growth, stabilization, purification, washing, drying, and storage. Each stage can influence the environmental footprint and quality of the final material.

A genuinely greener nanomaterial process therefore requires attention to both the chemistry and the process engineering. A biological extract may reduce the need for a synthetic reducing agent, but the process should still be evaluated for water consumption, extraction energy, purification requirements, waste generation, material yield, stability, and downstream processing. This broader view helps distinguish a genuinely sustainable process from one that is simply described as green because a biological ingredient has been included [4,19].

Key Green Chemistry Considerations in Nanomaterial Synthesis

Prevention of waste generation through efficient reaction design and minimal purification losses.

Maximum utilization of starting materials so that valuable precursors are converted efficiently into the desired nanomaterial [18,20].

- Reduction or elimination of hazardous reducing, stabilizing, and processing reagents.
- Use of safer solvents and reaction conditions whenever technically feasible.
- Reduction of energy requirements by favoring mild temperature, pressure, and reaction conditions.
- Use of renewable biological feedstocks such as plants, algae, microorganisms, and biomass.
- Reduction of unnecessary synthetic and purification steps.
- Use of catalysts and efficient reaction pathways to improve conversion and selectivity.
- Design of nanomaterials with safer physicochemical characteristics where the intended application permits.
- Consideration of degradation, recycling, disposal, and end-of-life behavior.
- Real-time monitoring and process control to improve consistency and reduce failed batches.
- Minimization of environmental and occupational hazards throughout the process.

Green Metrics and Process Evaluation: Evaluation of green synthesis should extend beyond the identity of the reducing agent. Useful process-level considerations include process mass intensity, reaction mass efficiency, energy consumption, solvent use, waste generation, purification requirements, and the environmental implications of raw-material production. These measures are important because two biological synthesis routes can differ considerably in their overall sustainability even when both use plant extracts [11].

3. BIOLOGICAL ROUTES FOR GREEN NANOMATERIAL SYNTHESIS

Biological synthesis uses living systems or biological materials as sources of reducing, capping, stabilizing, or functional molecules. This review considers three major routes: plant-mediated, microbial, and algae-mediated synthesis. The chemical composition of the biological source strongly influences nanoparticle formation and therefore must be considered when evaluating reproducibility [21].

3.1. Plant-Mediated Synthesis: Plant-mediated synthesis is one of the most widely investigated biological approaches for nanoparticle production. Plant tissues contain mixtures of primary and secondary metabolites, and their composition depends on species, plant part, geographical origin, soil characteristics, season, growth conditions, extraction method, and

storage. Leaves, stems, roots, bark, flowers, fruits, seeds, and peels can therefore provide different chemical environments for nanoparticle formation.

In a general process, a plant extract is prepared using water or another suitable solvent and subsequently mixed with an appropriate precursor salt. Biomolecules present in the extract can interact with metal ions and donate electrons, initiating reduction and nucleation. Once nanoscale nuclei are formed, additional biomolecules can adsorb onto their surfaces and help limit uncontrolled growth or aggregation. This combination of reduction and surface stabilization is one of the central features of plant-mediated synthesis.

For example, gold ions can be reduced from the ionic state to elemental gold, followed by nucleation and growth of gold nanoparticles. Comparable reduction processes can occur during the formation of silver and copper nanoparticles. For metal oxide nanoparticles, additional stages such as hydrolysis, precipitation, drying, and calcination may be involved. Plant-mediated synthesis offers several practical advantages: it can use renewable raw materials, may require relatively mild conditions, can reduce dependence on conventional reducing and capping agents, and can be comparatively simple and economical. However, variability in plant chemistry can produce changes in nanoparticle size, morphology, surface chemistry, and colloidal stability. Standardized extract preparation and characterization are therefore essential for reproducibility [31].

3.2. Microbial Synthesis: Bacteria, fungi, yeast, and other microorganisms can function as biological factories for nanoparticle synthesis. Microorganisms may produce extracellular or intracellular enzymes, proteins, peptides, and metabolites that participate in metal-ion reduction and particle stabilization. Depending on the organism and reaction conditions, nanoparticle formation may occur outside the cells or within cellular structures.

Microbial synthesis can provide biological control over nanoparticle formation, but maintaining cultures requires careful attention to growth conditions, nutrient availability, contamination control, and process optimization. Consequently, microbial routes may be more technically demanding than plant-mediated synthesis in some settings [43].

3.3. Algae-Mediated Synthesis: Algae contain proteins, carbohydrates, pigments, polyphenols, and other biomolecules that can participate in nanoparticle formation. Both microalgae and macroalgae have been investigated as renewable biological resources for metal and metal oxide nanoparticle synthesis. Their availability and biomass-producing capacity make algae attractive for sustainable material development.

Algae-mediated nanoparticles have potential relevance to environmental remediation, antimicrobial materials, catalysis, and sensing. As with plant systems, however, the composition of algal biomass and the selected processing conditions can affect nanoparticle characteristics and should therefore be standardized [42].

4. MECHANISTIC BASIS OF BIOLOGICAL NANOPARTICLE FORMATION

Biological nanoparticle formation can be viewed as a sequence of overlapping chemical and physicochemical events rather than a single reaction. The initial stage involves interaction between biological molecules and the nanoparticle precursor. Reducing molecules may transfer electrons to metal ions, generating atoms that begin to cluster. Once sufficiently stable nuclei are formed, further atoms may deposit on the nuclei and promote particle growth.

At the same time, proteins, polyphenols, sugars, organic acids, and other biomolecules can adsorb onto the particle surface. These molecules may influence nucleation and growth and can provide steric or electrostatic stabilization. The final size, shape, aggregation state, and surface chemistry are therefore determined by the balance among precursor concentration, biological composition, reaction conditions, nucleation rate, growth rate, and stabilization.

This mechanistic view is important for sensor development because the surface chemistry of a green-synthesized nanoparticle is not necessarily identical to that of a particle prepared using a conventional synthetic route. Residual biological molecules can contribute functional groups and may influence analyte recognition, dispersion, electron transfer, and interactions with biological recognition elements [30].

5. MAJOR CLASSES OF GREEN-SYNTHESIZED NANOMATERIALS

Different nanomaterial classes offer different combinations of optical, electrical, catalytic, magnetic, and surface properties. The selection of a nanomaterial for sensing should therefore be based on the target analyte, recognition mechanism, signal-transduction strategy, sample matrix, and required detection performance [7,8,15,18,25,30].

Silver Nanoparticles: Silver nanoparticles are among the most extensively studied green-synthesized nanomaterials. Their strong optical response, high surface area, catalytic behavior, and antimicrobial properties make them attractive for sensing and biosensing. Plant-derived compounds can participate in their formation and stabilization, potentially leaving biologically derived functional groups at the nanoparticle surface.

In colorimetric systems, changes in nanoparticle aggregation or surface interaction can alter the optical response. In electrochemical systems, the large surface area and catalytic properties can contribute to signal generation. The suitability of silver nanoparticles must nevertheless be considered together with their stability and potential biological or environmental effects [38,43].

Gold Nanoparticles: Gold nanoparticles possess distinctive optical and surface properties that make them particularly valuable in colorimetric, fluorescence, electrochemical, and biosensing platforms. Plant-derived phytochemicals can participate in both the reduction of gold ions and stabilization of the resulting particles. Phenolic compounds are especially relevant because of their reducing capability and their ability to interact with nanoparticle surfaces.

The localized surface plasmon resonance of gold nanoparticles is highly sensitive to changes in particle aggregation, surface adsorption, and the refractive environment surrounding the particles. These changes can be translated into spectral shifts or visible color responses. This property provides a useful basis for simple colorimetric detection systems. [5]

Zinc Oxide Nanoparticles: Zinc oxide nanoparticles are semiconducting materials with photocatalytic, optical, and antimicrobial properties. Green synthesis using plant extracts has been explored as a route to reduce reliance on hazardous synthetic chemicals. Their semiconducting behavior can facilitate charge transfer in electrochemical and optical sensors. The relatively large surface area of zinc oxide nanoparticles also provides opportunities for immobilization of enzymes, antibodies, nucleic acids, and other recognition molecules. However, particle size and morphology can vary with extract composition and synthesis conditions, making careful process control necessary [20,25].

Iron Oxide Nanoparticles: Iron oxide nanoparticles, particularly magnetite and related iron oxide phases, are attractive because of their magnetic behavior. Magnetic separation can be used to recover nanoparticles from complex samples, concentrate target analytes, or simplify sample preparation. These characteristics create opportunities in separation, preconcentration, biosensing, and environmental monitoring [41].

Copper and Copper Oxide Nanoparticles: Copper and copper oxide nanoparticles exhibit catalytic, optical, electrical, and antimicrobial characteristics. Their catalytic activity can support electrochemical sensing and catalytic colorimetric assays. Green synthesis using plant-derived compounds can reduce dependence on conventional reducing agents. At the same time, copper-based nanomaterials require careful assessment of stability and toxicity because dissolved copper ions can contribute to biological and environmental effects. Sensor design should therefore consider not only analytical performance but also material stability and safe handling [25]

Carbon-Based Nanomaterials: Carbon-based nanomaterials include graphene, graphene oxide, reduced graphene oxide, carbon dots, and related structures. Their high surface area and electrical and optical properties make them useful in electrochemical and fluorescence sensing. Carbon dots are particularly attractive for fluorescence applications because their optical response can be modified through surface functionalization and interaction with target analytes [15]. Green approaches have increasingly explored renewable biomass and biological carbon sources for producing carbon-based nanomaterials. Such approaches connect renewable feedstocks with functional carbon materials and may contribute to more sustainable fluorescent and electrochemical sensing platforms shown in Table 1.

Table 1: Comparison of major green-synthesized nanomaterials and their sensing applications.

Nanomaterial	Key properties	Green synthesis sources	Sensor platforms	Representative applications
Silver nanoparticles (AgNPs)	Optical, catalytic, antimicrobial, high surface area	Plants, microorganisms, algae	Colorimetric, electrochemical, biosensors	Heavy metals, pathogens, pollutants, antimicrobial sensing
Gold nanoparticles (AuNPs)	Localized surface plasmon resonance, catalytic and surface properties	Plant extracts and other biological resources	Colorimetric, optical, fluorescence, electrochemical, biosensors	Metal ions, nucleic acids, biomarkers, analytical detection
Zinc oxide nanoparticles (ZnO)	Semiconducting, photocatalytic, optical, antimicrobial	Plant extracts and biological materials	Electrochemical and optical sensors	Chemical analytes, biomolecules, environmental monitoring
Iron oxide nanoparticles	Magnetic response, surface activity, separability	Plants, microorganisms and other biological routes	Magnetic-assisted and biosensing platforms	Separation, preconcentration, environmental and biological analysis
Copper/copper oxide nanoparticles	Catalytic, electrical, optical, antimicrobial	Plant-derived compounds and biological resources	Electrochemical and colorimetric sensors	Pollutants, catalytic assays and chemical detection
Carbon-based nanomaterials	High surface area, electrical and optical properties	Renewable biomass and biological carbon sources	Fluorescence and electrochemical sensors	Environmental analytes, biomolecules and fluorescence detection

6. CHARACTERIZATION OF GREEN-SYNTHEZED NANOMATERIALS

Comprehensive characterization is essential for understanding nanoparticle formation, establishing material quality, comparing different synthesis conditions, and assessing reproducibility. No single characterization technique provides a complete description of a nanomaterial. Instead, complementary methods are generally required to evaluate optical

properties, functional groups, crystal structure, morphology, particle size, colloidal stability, elemental composition, and surface chemistry [7,19,23,33].

Ultraviolet-Visible Spectroscopy: Ultraviolet-visible spectroscopy is widely used to monitor nanoparticle formation and optical behavior. Metallic nanoparticles such as gold and silver display characteristic surface plasmon resonance bands. Changes in peak position, intensity, or bandwidth can provide qualitative information about particle formation, growth, aggregation, and changes in the surrounding chemical environment [33].

Fourier-Transform Infrared Spectroscopy: Fourier-transform infrared spectroscopy is used to identify functional groups associated with plant metabolites or other biomolecules present before and after nanoparticle synthesis. Changes in absorption bands can provide evidence that hydroxyl, carbonyl, amine, or other functional groups participate in reduction or become associated with the nanoparticle surface [33].

X-Ray Diffraction: X-ray diffraction is used to determine crystalline structure and phase composition. Diffraction patterns can confirm the presence of crystalline phases and, when appropriate analytical models are applied, provide estimates of crystallite size. X-ray diffraction is therefore useful for determining whether the expected crystalline material has formed [33].

Transmission Electron Microscopy and Scanning Electron Microscopy: Transmission electron microscopy provides direct information about nanoscale particle morphology and dimensions, whereas scanning electron microscopy can reveal surface morphology and particle distribution over larger areas. These techniques are important for determining whether the synthesis produces approximately spherical, irregular, aggregated, or otherwise distinctive particle morphologies [33].

Dynamic Light Scattering: Dynamic light scattering measures hydrodynamic particle size and polydispersity in suspension. Because the measured hydrodynamic diameter reflects the particle together with associated solvent and surface layers, it can differ from the physical dimensions observed by electron microscopy. The technique is especially useful for evaluating aggregation and dispersion stability [7].

Zeta-Potential Analysis: Zeta-potential analysis provides information about the electrostatic characteristics of a nanoparticle suspension. Higher absolute zeta-potential values can indicate stronger electrostatic stabilization, although overall colloidal stability can also depend on steric effects, adsorbed biomolecules, ionic strength, and other biochemical interactions [7].

Elemental and Surface Analysis: Energy-dispersive X-ray spectroscopy, X-ray photoelectron spectroscopy, inductively coupled plasma-based methods, and related techniques can provide complementary information about elemental composition, oxidation state, surface chemistry, and the presence of associated elements [33]. Such analyses are particularly valuable when biological molecules are expected to remain associated with the nanoparticle surface.

7. NANOMATERIALS AS FUNCTIONAL COMPONENTS OF SENSORS

Nanomaterials can improve sensor performance through several related mechanisms. Their large surface area creates additional sites for analyte interaction. Their electronic properties can facilitate charge transfer, while catalytic surfaces can accelerate signal-producing reactions. Optical nanomaterials can transform molecular recognition events into measurable changes in absorption, scattering, fluorescence, or colour shown in Figure 1 [21,26].

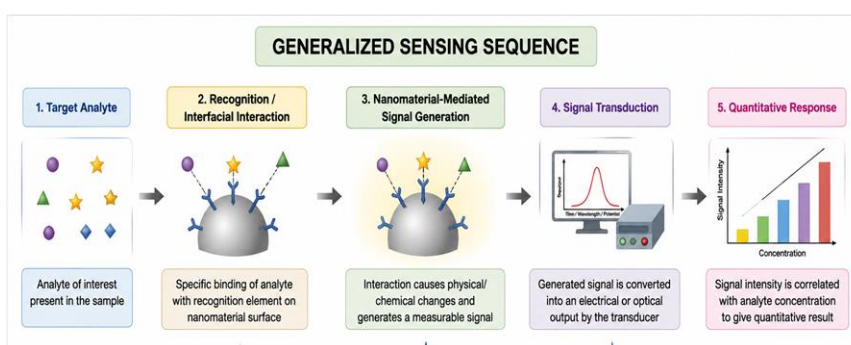


Figure 1. Generalized sensing sequence illustrating the stepwise process from target analyte recognition to nanomaterial-mediated signal generation, signal transduction, and quantitative detection through electrical, optical, fluorescent, colorimetric, or electrochemiluminescent responses.

A generalized sensing sequence can be represented as: target analyte → recognition or interfacial interaction → nanomaterial-mediated signal generation → signal transduction → quantitative response. The final signal may be electrical, optical, fluorescent, colorimetric, or electrochemiluminescent depending on the sensing platform [15,20]

8. ELECTROCHEMICAL SENSORS

Electrochemical sensors detect changes in electrical parameters such as current, potential, impedance, or conductivity following interaction with an analyte. Nanomaterials can improve electrochemical performance by increasing the effective electrode surface area and facilitating electron transfer. Metallic nanoparticles can also function as electrocatalytic components, whereas graphene and related carbon materials can form conductive networks.

Green-synthesized nanoparticles can therefore be incorporated into modified electrodes for detecting a broad range of targets. Examples include heavy-metal ions, pesticides, phenolic pollutants, glucose, dopamine, uric acid, pathogenic microorganisms, pharmaceutical compounds, and cancer-associated biomarkers [2,34,37].

In biosensor formats, biological recognition elements such as enzymes, antibodies, aptamers, deoxyribonucleic acid, ribonucleic acid, or receptors can be immobilized on nanostructured surfaces. The nanoparticle layer can provide a favorable interface and help amplify or stabilize the analytical signal [22,26].

9. OPTICAL AND COLORIMETRIC SENSORS

Optical sensing is particularly attractive for green nanomaterials because many nanoparticles exhibit strong and tunable optical responses. Gold and silver nanoparticles display localized surface plasmon resonance, a collective optical phenomenon that is sensitive to the particle environment.

When nanoparticles aggregate, separate, or interact with target molecules, the plasmonic environment changes. This may produce a shift in the optical spectrum or a visible color change. A generalized colorimetric mechanism can therefore be described as: analyte + functionalized nanoparticle → aggregation, disaggregation, or surface interaction → change in localized surface plasmon resonance → measurable color response [14].

Colorimetric systems are attractive for field and decentralized applications because some can be interpreted visually without sophisticated instrumentation. Green-synthesized gold nanoparticles have been investigated in strategies for detecting ions, fluoride-related systems, nucleic acids, and other target analytes [5,6].

10. FLUORESCENCE-BASED SENSORS

Fluorescence sensors provide high analytical sensitivity and can be adapted for biological and environmental measurements. Green-derived carbon dots and other fluorescent nanomaterials can be designed to respond to target molecules through changes in fluorescence intensity or emission wavelength [10,26].

- Fluorescence quenching, in which interaction with the analyte decreases emission intensity.
- Fluorescence enhancement, in which target interaction increases the measured signal.
- Förster resonance energy transfer between a donor and an acceptor component.
- Electron-transfer interactions that modify the excited-state behavior of the sensing system.
- Surface adsorption that changes the local environment of the fluorescent material.
- Chemical transformation of a fluorescent probe that changes its optical response.

Renewable biological materials can serve as carbon precursors for carbon-dot preparation, linking biomass utilization with fluorescence-based sensing. The final performance, however, depends on particle surface chemistry, optical stability, target recognition, and the composition of the sample matrix.

11. GREEN NANOMATERIALS IN BIOSENSOR DEVELOPMENT

Biosensors combine a biological recognition component with a physical or chemical transducer. Nanomaterials can improve this interface by providing a high-surface-area platform for biomolecule immobilization and by facilitating signal transduction. The recognition element determines the target specificity, while the nanomaterial contributes to signal generation or amplification [21,29,30].

Enzyme-Based Biosensors: Enzymes provide high specificity toward their substrates. Nanostructured surfaces can facilitate enzyme immobilization and improve electron transfer between enzymatic reactions and the transducer. This combination can support sensitive detection of small molecules and metabolites.

Immunosensors: Immunosensors use antibodies to recognize specific antigens or biomarkers. Nanoparticle-based surfaces can provide a larger interface for antibody immobilization and may increase the measurable signal generated after target binding.

Aptamer-Based Sensors: Aptamers are short nucleic-acid sequences selected for their ability to recognize specific targets. Their integration with nanomaterials provides opportunities for highly selective sensing and can be adapted to optical or electrochemical transduction strategies.

Deoxyribonucleic Acid and Ribonucleic Acid Sensors: Nanoparticles can interact with nucleic acids through hybridization, adsorption, or surface functionalization. Such systems are useful for pathogen detection, molecular diagnostics, and biomarker analysis. The choice of nanomaterial and recognition chemistry determines how efficiently a target sequence can be captured and converted into a measurable response.

12. ENVIRONMENTAL APPLICATIONS

Environmental monitoring is one of the most important application areas for nanomaterial-based sensing because contamination may occur over large geographic areas and may require rapid analysis. Portable green sensors could provide useful screening capabilities in locations where conventional laboratory-based analysis is difficult or slow [28,41].

Heavy-Metal Detection: Lead, mercury, cadmium, arsenic, chromium, and other metal contaminants can enter water and soil through natural processes and human activities. Green nanomaterial-based sensors can support their detection using electrochemical, colorimetric, or fluorescence mechanisms. Nanostructured surfaces can improve analyte interaction and help generate stronger analytical responses.

Pesticide Detection: Agricultural pesticides may enter soil, water, crops, and food systems. Nanobiosensors incorporating enzymes, antibodies, or aptamers can provide recognition of selected pesticide molecules. The combination of biological specificity and nanomaterial-assisted signal generation can support rapid screening.

Pathogen Detection: Nanomaterial-based biosensors can detect bacterial and viral pathogens using antibodies, deoxyribonucleic acid, ribonucleic acid, or aptamer recognition. Rapid detection is valuable in environmental water monitoring and other settings where early identification of contamination is important.

Organic Pollutants: Phenolic compounds, dyes, pharmaceutical residues, and other organic pollutants can be monitored using nanostructured electrochemical and optical systems. Catalytic nanomaterials can enhance reaction-based signals, while optical materials can provide changes in absorption, fluorescence, or color following analyte interaction.

13. HEALTHCARE AND BIOMEDICAL APPLICATIONS

Healthcare diagnostics require rapid, sensitive, and sufficiently selective detection of disease-associated biomarkers. Nanomaterials can increase analytical performance by providing high surface area, improving biomolecule immobilization, and supporting signal amplification.

Potential targets include glucose, cholesterol, uric acid, cancer biomarkers, inflammatory biomarkers, hormones, proteins, deoxyribonucleic acid, ribonucleic acid, and pathogen-derived biomarkers. Nanobiosensors may support point-of-care diagnosis because nanoscale sensing components can be incorporated into miniaturized analytical systems.

In cancer research, nanomaterial-based biosensors can be designed to detect proteins, nucleic acids, circulating biomarkers, and other disease-associated molecules. Green-synthesized nanoparticles may provide a more sustainable material platform when their synthesis, stability, toxicity, and analytical performance are adequately characterized [20,32].

14. FOOD SAFETY APPLICATIONS

Food contamination by pathogens, pesticides, toxins, allergens, heavy metals, and adulterants represents an important public-health concern. Green nanomaterial-based sensors can provide rapid screening of food samples, potentially reducing the time required for preliminary assessment.

Colorimetric sensors are attractive for simple visual screening, whereas electrochemical sensors can provide quantitative measurements. Nanoparticle-based recognition systems may also be incorporated into portable devices for monitoring contaminants during food production, processing, transportation, and storage [28,32].

15. AGRICULTURAL APPLICATIONS

Agriculture can benefit from sensors capable of monitoring soil nutrients, pesticides, pathogens, heavy metals, and plant-associated biomarkers. Nanomaterial-based sensors may support rapid or near-real-time assessment of agricultural environments and contribute to precision agriculture.

The integration of sensing components with wireless communication and smartphone technologies could enable decentralized data collection. Green synthesis is particularly relevant to agriculture because renewable biological materials may be used as functional sources for sensing components, potentially reducing the environmental burden associated with conventional synthesis [13].

16. INDUSTRIAL AND FIELD-ORIENTED APPLICATIONS

Beyond environmental, healthcare, food, and agricultural uses, green nanomaterial-based sensors have potential relevance to industrial monitoring. Their catalytic, optical, electrical, and surface properties can be exploited for detecting process-related compounds and contaminants. Portable sensor designs are especially attractive when frequent laboratory analysis is impractical.

Field-oriented implementation requires more than high analytical sensitivity. Devices must also provide stable calibration, adequate selectivity, mechanical robustness, simple operation, acceptable storage stability, and reproducible manufacturing. These requirements highlight the importance of integrating material science with sensor engineering and validation [12].

17. ADVANTAGES OF GREEN NANOMATERIAL-BASED SENSORS

- Green nanomaterial-based sensors combine the functional advantages of nanomaterials with the potential process advantages of biological synthesis. Their major benefits can be summarized as follows:
 - Reduced use of hazardous chemicals because biological extracts may replace or reduce conventional reducing and stabilizing agents.
 - Use of renewable raw materials such as plants, algae, microorganisms, and biomass.
 - Potentially low-cost synthesis using relatively mild processing conditions.
 - Improved surface functionality because biomolecules remaining on nanoparticle surfaces can provide useful chemical groups.
 - High sensitivity associated with large active surface areas and efficient signal transduction.
 - Rapid detection through optical, colorimetric, fluorescent, and electrochemical responses.
 - Miniaturization into portable, microfluidic, and point-of-care formats.

- Versatility for detecting chemical, environmental, biological, and clinically relevant targets.
- Potential for decentralized analysis outside conventional laboratory environments.
- Potential reduction of waste, energy demand, and environmental burden when the complete process is appropriately designed [35].

18. CHALLENGES AND LIMITATIONS

Despite substantial progress, several barriers must be addressed before green nanomaterial-based sensors can achieve broad commercial and field implementation. The major challenges are not limited to nanoparticle synthesis; they also include material consistency, sensor fabrication, sample complexity, long-term stability, safety, and regulatory validation [35,36].

Reproducibility: The chemical composition of plant extracts can vary significantly between batches. Differences in plant species, geographical origin, season, cultivation conditions, extraction procedure, and storage can alter the concentration of active metabolites. As a result, nominally identical synthesis protocols may generate nanoparticles with different sizes, shapes, surface chemistry, and biological properties

Scalability: A synthesis procedure that performs well at laboratory scale may not produce identical materials during large-scale production. Reactor design, mixing, heat transfer, precursor addition, extract preparation, purification, and drying can all influence the final product. Scale-up therefore requires process engineering rather than simple multiplication of laboratory quantities.

Standardization: Standardized procedures are required for plant selection, extraction, phytochemical profiling, precursor concentration, reaction conditions, purification, storage, and nanoparticle characterization. Without standardization, comparison among studies and translation into manufacturing can be difficult.

Stability: Nanoparticles may aggregate during storage or exposure to environmental or biological media. Changes in pH, ionic strength, temperature, and sample composition can influence dispersion and surface interactions. Long-term stability is therefore a central requirement for practical sensor deployment.

Toxicity and Safety: The term green synthesis does not automatically mean that a nanoparticle is non-toxic. Biological and environmental effects depend on particle composition, size, shape, surface chemistry, dose, exposure route, and environmental conditions. Toxicity assessment should therefore accompany the development of green nanomaterials, especially when biomedical or environmental applications are proposed.

Performance in Complex Biological and Environmental Samples: Real samples contain numerous potentially interfering substances. A sensor that performs well in a clean laboratory buffer may show reduced selectivity or sensitivity in complex matrices. Real-sample validation, interference studies, recovery assessment, and comparison with established analytical methods are therefore important steps toward practical application.

Commercial Translation and Regulatory Considerations: Commercial translation requires reproducible manufacturing, stable materials, reliable calibration, adequate selectivity, robust operation, predictable shelf life, and validation against established analytical methods. Green synthesis must therefore be considered as one component of a broader development pathway that includes quality control, safety evaluation, device engineering, and performance validation [44,45,46,47]

19. CONCLUSION

The integration of green chemistry, nanotechnology, and sensing technology provides an important pathway toward sustainable analytical systems. Biological resources such as plant extracts, microorganisms, algae, and renewable biomass can provide functional molecules capable of supporting nanoparticle formation while reducing dependence on conventional hazardous reagents. Green-synthesized silver, gold, zinc oxide, iron oxide, copper and copper oxide, and carbon-based nanomaterials possess physicochemical properties that are highly advantageous for sensing.

The high surface area, catalytic activity, optical behavior, conductivity, magnetic response, and surface functionality of these materials can contribute to improved electrochemical, optical, colorimetric, fluorescence, and biosensor platforms. Their potential applications extend across environmental monitoring, healthcare diagnostics, food safety, agriculture, and industrial analysis. Portable and decentralized systems are especially promising because nanomaterial-enabled signal generation can be integrated into compact sensing formats [40].

At the same time, green synthesis should not be considered environmentally sustainable solely because a biological extract is used. Reproducibility, energy consumption, waste generation, toxicity, scalability, stability, standardization, and life-cycle impacts must all be evaluated. The future of the field therefore depends on a transition from proof-of-concept demonstrations toward standardized, mechanistically understood, scalable, and validated sensing systems.

Future research should focus on standardized synthesis protocols, detailed understanding of phytochemical-nanoparticle interactions, scalable production, rigorous safety assessment, real-sample validation, and portable sensor development. Integration with smartphones, microfluidics, artificial intelligence, machine learning, and Internet-of-Things technologies may further expand the practical utility of green nanomaterial-based sensing. The convergence of these areas could contribute to sensitive, selective, affordable, portable, and environmentally responsible analytical technologies [38].

20. FUTURE PERSPECTIVES

The future of green nanomaterial-based sensing is likely to depend on convergence among sustainable materials chemistry, nanotechnology, sensor engineering, digital technologies, and data science. Several directions are particularly promising [16,17,32,38,40].

Smartphone-Integrated Sensors: Modern smartphones contain cameras, processors, wireless communication, and image-processing capabilities. These functions can be coupled with colorimetric and optical nanomaterial-based sensors to support decentralized measurements. Smartphone-assisted interpretation could reduce dependence on specialized laboratory instruments for selected screening applications.

Microfluidic Platforms: Microfluidic systems can reduce sample and reagent consumption while enabling controlled handling and rapid analysis. Combining microfluidics with green nanomaterials may facilitate compact environmental and biomedical testing platforms.

Artificial Intelligence and Machine Learning: Artificial intelligence and machine-learning approaches can assist in interpreting complex electrochemical, spectral, and colorimetric responses. Such methods may help classify samples, identify patterns, and estimate analyte concentrations when the relationship between signal and target concentration is complex.

Multiplexed Sensing: Future sensor systems may be designed to detect several analytes simultaneously. Nanomaterials with different optical or electrochemical signatures can be integrated into multiplexed platforms, enabling broader chemical or biological profiling within a single analytical device.

Sustainable-by-Design Nanomaterials: Future research should move beyond greener synthesis and consider the complete life cycle of a nanomaterial. Raw-material sourcing, synthesis, purification, application, degradation, recycling, and disposal should be considered during material design. This approach can help align nanomaterial development with broader sustainability objectives.

Standardized Green Synthesis and Quality Control: Standardized protocols for extract preparation, phytochemical profiling, nanoparticle characterization, green-metric evaluation, and sensor validation will be essential for improving reproducibility. Mechanistic understanding of phytochemical-nanoparticle interactions will also help establish more predictable relationships between biological source, nanoparticle structure, and sensing performance.

Integration with Connected and Portable Technologies: Combining green nanomaterial sensors with smartphones, microfluidics, wireless communication, artificial intelligence, and Internet-of-Things technologies could support distributed monitoring networks. Such systems may be particularly useful for environmental surveillance, agricultural monitoring, food safety, and point-of-care applications where rapid and decentralized measurements are valuable.

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