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Green Synthesis of Nanomaterials and Their Analytical Applications: A Review of Sustainable Routes and Sensing Performance

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Abstract

Green synthesis of nanomaterials has emerged as a promising approach for preparing functional nanostructures in an environmentally safe and sustainable manner. This review examines the mechanistic aspects of producing green nanomaterials, focusing on the role of reducing and stabilizing biological agents in regulating formation, growth, and surface activation. It also thoroughly investigates the structure-property relationships that govern the analytical performance of green-synthesized nanomaterials (e.g., silver and gold nanoparticles, zinc oxide and iron oxide nanoparticles, and carbon dots), emphasizing how surface chemistry, particle size, and crystallinity influence sensing efficiency. Environmental and biological detection is a key focus. The review discusses in detail the integration of green nanomaterials into electrochemical, optical, and colorimetric sensing systems. Green methods often achieve superior analytical performance, enhanced biocompatibility, and greater sustainability, as demonstrated by comparisons between conventionally synthesized and green nanomaterials. This work presents future visions for developing hybrid synthesis methodologies and establishing clearer standard approaches, while also discussing current challenges related to reproducibility and industrial scalability. The analysis comprehensively demonstrates that environmentally friendly nanomaterials represent a promising and practical foundation for developing future analytical techniques that align with the principles of sustainable green chemistry and support its applied trends.

Keywords

Analytical Applications,
Green Synthesis,
Nanomaterials,
Sensing,
Surface Chemistry

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Introduction

Nanomaterials synthesized using green methods have garnered significant attention in recent decades due to their distinctive physical and chemical properties compared to their conventional counterparts. Their integration into diverse industrial and laboratory applications, particularly in analytical chemistry and chemical sensing, is facilitated by their unique characteristics such as high surface area-to-volume ratio, size-dependent optical behavior, and excellent catalytic activity. The physical and chemical methods used in conventional nanomaterial synthesis have raised concerns regarding biosafety and environmental impact, as these methods often require substantial energy inputs (heat or pressure), hazardous reducing agents, and non-biodegradable stabilizers (Iravani, 2011). Therefore, this approach aims to align nanomaterial manufacturing with the principles of green chemistry and sustainability. Unlike conventional techniques, green synthesis utilizes biological systems, including microbes, plants, and natural biopolymers, as stabilizing and reducing agents. This dual purpose reduces the need for hazardous chemicals while maintaining control over particle size and shape, enabling the production of nanoparticles in mild environments that do not require high temperatures and pressures. These environmentally friendly methods not only replace traditional reagents but also fundamentally alter the formation and growth dynamics of nanomaterials, as numerous studies have shown (Singh et al., 2018).

Among the most important biological systems, plant systems have gained particular importance due to their natural phytochemical composition and ease of use. Extracts derived from leaves, roots, seeds, or fruits contain a variety of biomolecules capable of catalyzing the reduction of various metal ions and stabilizing the resulting nanoparticles. Beyond sustainability considerations, these biomolecule-mediated processes often produce nanomaterials with enhanced surface functionalization, which is particularly beneficial for analytical and sensing applications, where surface interactions control the sensitivity and selectivity of the prepared materials (Khan et al., 2019).

In the field of analysis, the integration of environmentally friendly nanomaterials into sensing platforms has shown promising results in detecting organic pollutants such as dyes, heavy metal ions, biomolecules, and pharmaceuticals. These nanomaterials often offer better biocompatibility and a lower environmental impact than their conventionally synthesized counterparts, while exhibiting similar or even higher sensitivity. Consequently, green nanotechnology is gaining increasing recognition as a technologically competitive strategy in analytical chemistry, as well as an ethical and environmentally sound option (Singh et al., 2018).

Despite the rapid growth of the literature on green synthesis, many existing reviews treat synthesis routes, biomedical use, or environmental remediation separately, and recent overviews often concentrate on a single sensing mode or analyte class, for example voltammetric biosensors based on plant-extract-derived metal nanoparticles (Lazarova et al., 2023) or the detection of heavy metal ions with natural and engineered nanomaterials (Joseph et al., 2022). An integrated analysis, however, connecting the mechanisms of biological reduction and capping with the analytical performance which is governed by the structure–property relationships, is still needed. This review will focus on three gaps. First, it relates the function of biological agents of reducing and stabilizing to the surface chemistry, size and crystallinity which determine sensitivity and selectivity. Secondly, it confirms electrochemical, optical and colorimetric platforms in a single framework and, if available, compares them to conventionally synthesized materials, using summary tables of the synthesis conditions and analytical performance. Third, it explores the challenges of transferability of green-nanomaterial based sensors from the lab to practice, such as challenges of reproducibility, real sample validation, scalability and standardization.

2. Mechanisms of Green Synthesis of Nanomaterials

A series of connected physicochemical processes that take place in reaction settings drawn from biology control the green synthesis of nanomaterials. Green methods rely on multifunctional proteins that simultaneously initiate metal ion reduction and govern

nanoparticle growth, in contrast to conventional chemical synthesis, where reduction and stabilization are usually driven by distinct reagents. A characteristic of physiologically mediated synthesis, this inherent link between reduction and stabilization plays a major role in determining the structural and functional characteristics of the final nanomaterials.

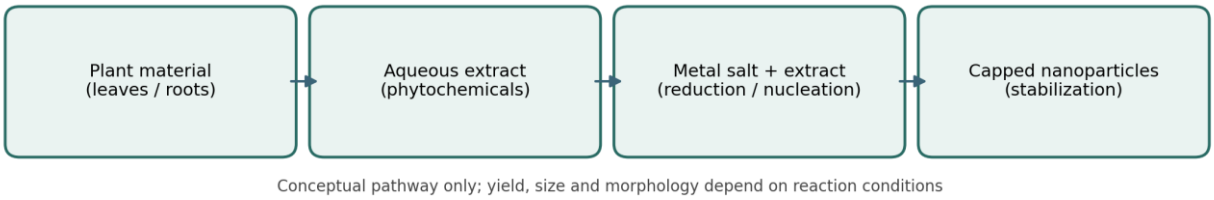


Figure 1: Original conceptual schematic of plant-mediated metal nanoparticle synthesis (prepared for this review; not experimental data).

Figure 1 schematically illustrates the green synthesis process using various plants, showing the stages of metal ion reduction, nucleation, particle formation, and surface stabilization. A protective organic layer forms upon adsorption of biomolecules onto the nanoparticle surface, preventing agglomeration and ensuring stability. Due to its ease of use and scalability, plant-based green synthesis is the most studied approach. According to Khan *et al.* (2019), the phytochemical composition of plant extracts significantly influences the size distribution, crystallinity, and shape of the nanoparticles, as well as their size-dependent optical properties, resulting in different colors due to absorption in the visible light spectrum. Extracts rich in phenolic compounds typically produce smaller, more homogeneous nanoparticles, which is particularly beneficial for analytical sensing applications.

Green routes using bacteria, fungi and algae, as well as plant extracts, are discussed in the wider literature. Organism-dependent enzymes and metabolites may participate in intracellular or extracellular nanoparticle formation (Singh et al., 2018).

The balance between the extract components and the reaction conditions (pH, temperature, preparation time) directly influences the properties of the resulting particles, such as size, shape, and stability. Therefore, the use of plant extracts is not only an environmentally friendly alternative but also an efficient and controlled way to produce nanomaterials with wide-ranging applications in medicine, energy, and water treatment.

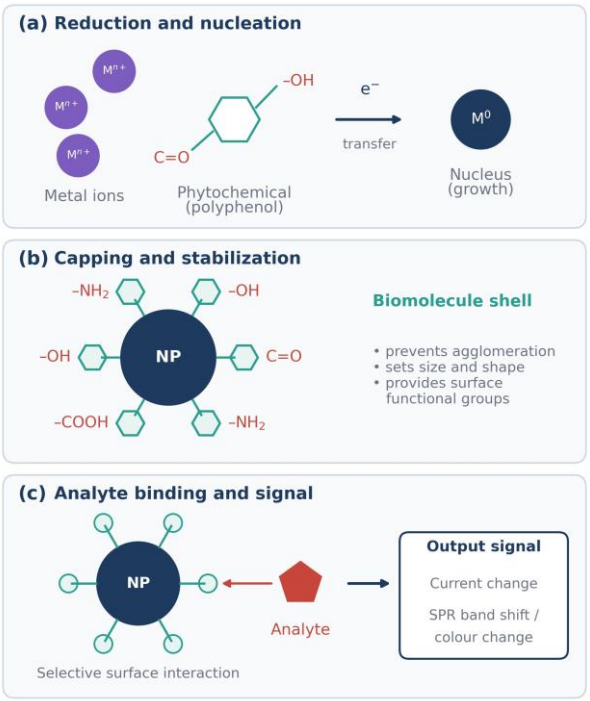


Figure 2: Functional-group interactions at the nanoparticle–biomolecule interface: (a) reduction and nucleation, (b) capping and stabilization, and (c) analyte binding and signal generation.

Figure 2 complements Figure 1 by focusing on the nanoparticle–biomolecule interface: functional groups of the biological agent (–OH, C=O, –NH_2, and –COOH) donate electrons during reduction, remain adsorbed as a capping shell that limits agglomeration and controls size and shape, and afterwards provide the binding sites through which analytes interact with the surface and generate the analytical signal. The surface chemistry and size of the nanoparticles, crucial factors in determining analytical sensitivity and selectivity, are directly influenced by these processes.

Overall, the preparation mechanism reveals that this method is a complex chemical approach that allows for precise control over the properties of nanoparticles, rather than simply being an environmentally friendly alternative. This type of control is essential for tailoring nanomaterials to high-performance analytical sensing applications.

Table 1 summarizes representative biological sources, precursors, and reaction conditions reported for green-synthesized nanomaterials used in sensing.

Table 1: Representative green synthesis routes, precursors, and conditions.

Biological source	Precursor / conditions	Product and reported features	Ref.
Plant extracts (leaf, root, seed, fruit)	Metal salt + extract; pH, temperature, and reaction time tune the outcome	Phenolic-rich extracts typically give smaller, more homogeneous nanoparticles	Khan et al., 2019
Bacteria, fungi, algae	Secreted enzymes and metabolites; intra- or extracellular reduction	High productivity and stability for fungal synthesis; proteins and polysaccharides stabilize particles	Singh et al., 2018; Singh et al., 2018; Singh et al., 2018
Murraya koenigii leaf (aqueous extract)	$AgNO_3$ + extract; photo-induced by sunlight (30 min)	Spherical AgNPs, mean size ≈ 8.6 nm (TEM); SPR band ≈ 430 nm	Kumar et al., 2017
Bistorta amplexicaulis root extract	Root extract as reducing and stabilizing agent	AgNPs characterized by UV–Vis, FT-IR, XRD, AFM, and zeta sizing; used as colorimetric Hg^{2+}/Pb^{2+} sensor	Ahmed et al., 2020
Waste tea (re-extraction)	Waste-tea extract as reducing and stabilizing agent	AgNPs used to modify a carbon paste electrode for amperometric glucose sensing	Üçdemir Pektaş et al., 2024

AgNPs, silver nanoparticles; SPR, surface plasmon resonance; TEM, transmission electron microscopy.

3. Types of Green-Synthesized Nanomaterials

The successful use of green preparation of biological materials such as plants and algae has contributed to the preparation of many nanomaterials such as metal nanoparticles, metal oxide nanoparticles, and carbon nanostructures. The quality of the prepared nanomaterial determines its analytical performance in terms of chemical selectivity, sensitivity, signal stability, and the required nanoscale size.

3.1 Metallic Nanoparticles

Due to their exceptional optical and electrochemical properties, metallic nanoparticles, particularly silver (Ag) and gold (Au), are among the most researched and environmentally friendly nanomaterials. They are ideal for optical sensing applications.

Rimsha et al. (2024) reported that the stability of silver nanoparticles depends on the organism characteristics, catalytic arrangement and genetics. Chemical reduction is the most efficient method, because it has a high production rate, is thermally stable and can be modified by adding a stabilizer. It's corrosive, energy consuming, and it causes chemical pollutants, however. High purity, uniform sized silver nanoparticles can be prepared using physical methods like atomization, laser ablation and arc discharge which does not involve the use of hazardous chemicals but is costly and has low production rate. Using lasers, UV light and sunlight, the photochemical method is expensive and time consuming but can provide homogeneity, uniform size and minimal agglomeration.

Gold nanoparticles are also widely used in biological and chemical sensors and their applications due to their unique chemical, optical, and catalytic properties. Their use is particularly prevalent in colorimetric assays because of their ease of fabrication, low cost, and ease of use. Importantly, the response of gold nanoparticle sensors is a visible colour change, which facilitates the interpretation of results, as demonstrated by Chang *et al.* (2019).

3.2 Metal Oxide Nanoparticles

In addition to their chemical stability, catalytic activity, and semiconducting properties, metal oxide nanoparticles — ZnO, CuO, and CeO_2 — have been classified using environmentally friendly chemical methods. These nanoparticles were synthesized and examined using various characterisation techniques, such as UV-Vis spectroscopy, infrared spectroscopy, X-ray diffraction, scanning electron microscopy, and

transmission electron microscopy with atomic force microscopy (Amina & Fadam, 2024).

Zinc oxide nanoparticles synthesized using environmentally friendly physical and chemical methods have demonstrated unique properties, including antibacterial and antioxidant properties, UV absorption, enhanced mechanical strength, and resistance to moisture and oxygen. These properties, along with their influence on the physical and chemical properties of composite nanofilms, make them highly useful for monitoring environmental pollution, as demonstrated by Abolfazl and Nazila (2024). Functional groups extracted from plants enhance the reactivity of the analyte and the charge transport efficiency on zinc oxide surfaces.

Environmentally friendly synthesis of IO nanoparticles (MIONPs) has been well investigated and their application in magnetic sensing (Minh et al., 2025) has been widely studied. Applications of MIONPs will need a reproducible manufacturing process and an exact control over the homogeneity of the particles, in terms of particle size, particle shape, composition, etc. The problem of reproducible nanoparticle manufacturing, however, continues to be an issue, as researchers have not been able to repeat their production and incorporate MIONPs in their applied study. Many efforts have been dedicated in recent years to understanding the manufacturing mechanisms and achieving high reproducibility and homogeneity of particles, with remarkable advances achieved in the use of MIONPs in the biomedical field (Minh et al., 2025).

3.3 Carbon-Based Green Nanomaterials

Fullerenes, carbon nanotubes, graphene and reduced carbon are carbon nanomaterials that are used in engineering and medicine. This study includes an introduction to their manufacturing methods and the applications that benefit from the use of C60 fullerene, carbon nanotubes, and graphene. The applications that are described are the use of C60 fullerene in organic solar cells, carbon nanotubes in sensors and biosensors, and graphene in batteries and supercapacitors. Other shared applications of these three material types, such as engineering and biomedical applications are also pointed out (Siqueira & Oliveira, 2017).

According to Liu *et al.* (2020), carbon dots, as a novel type of carbon nanomaterial, have garnered significant research attention for years due to their diverse physical and chemical properties and distinctive characteristics, such as good biocompatibility, unique optical properties, low cost, environmental friendliness, abundance of functional groups (e.g., amine, hydroxyl, and carboxyl), high stability, and electron mobility. Their fabrication methods and optical properties — including strong absorption, photoluminescence, and phosphorescence — support diverse applications, including optical sensors and anti-counterfeiting, energy (LEDs, catalysis, photovoltaics, and supercapacitors), and promising biomedicine.

3.4 Structure–Property Relationships

The physical properties of environmentally prepared nanomaterials, such as size, shape, crystallinity, and surface texture, significantly influence their analytical performance. These physical properties may vary considerably due to differences in reaction and preparation conditions, as well as variations in the biological sources used to manufacture these materials and the methods employed for their purification and extraction.

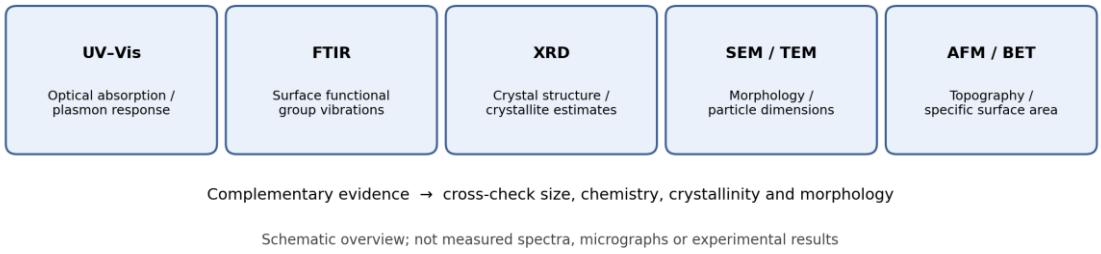


Figure 3: Original conceptual overview of complementary characterization methods (prepared for this review; no experimental spectra or microscopy images).

Figure 3 summarizes the complementary roles of UV-Vis, FTIR, XRD, SEM/TEM, AFM and BET characterization. UV-Vis probes optical absorption; FTIR identifies surface functional groups; XRD examines crystalline phases; electron and force microscopy assess morphology and topography; and BET estimates specific surface area. The scheme is illustrative and does not present measured sample data (Mourdikoudis et al., 2018).

This diversity of environmentally friendly nanomaterials provides a framework for developing high-performance analytical sensors tailored to specific target analytes used for chemical analysis.

4. Characterization Techniques of Green-Synthesized Nanomaterials

A number of microscopic methods, spectral diffraction methods, and spectroscopic analyses are used to confirm the effectiveness of green preparation of nanomaterials from different biological sources and to understand the reactions that take place within or on the surface of these materials, as particle size, shape, crystallinity, porosity, and surface volume are among the factors that greatly affect the analytical performance of the prepared nanomaterials.

4.1 UV-Visible Spectroscopy

Spectroscopic analysis (UV-Visible) of nanoparticles during green synthesis is a common and non-invasive method for tracking nanoparticle formation. The characteristic surface plasmon resonance (SPR) bands observed in metallic nanoparticles result from the collective oscillations of conduction electrons.

Mourdikoudis et al. (2018) reviewed complementary nanoparticle characterization techniques, including optical spectroscopy. For metallic nanoparticles, surface plasmon resonance peak positions and shapes may vary with particle size, morphology, aggregation state and surrounding medium; therefore, UV-Vis data should be interpreted alongside independent structural measurements.

The spectral analysis of ultraviolet and visible radiation is important for improving the conditions under which the raw materials are synthesized. The changes occurring in these spectra during the formation of plant- or algal-based nanomaterials provide indirect evidence of the reduction efficiency of these materials and thus reflect the reaction kinetics.

4.2 Fourier Transform Infrared Spectroscopy (FTIR)

Key groups responsible for the stability and significant reduction of green nanoparticles can be identified using Fourier transform infrared spectroscopy (FTIR). These groups include hydroxyl, carbonyl, amine, and carboxyl groups, and their association with the plant's chemical composition can be discussed.

According to Singh et al. (2018), FTIR spectra of bio- and plant-based nanoparticles shows substantial changes in the intensity of all the spectral bands, which can be attributed to the stretching vibrations of OH and NH groups. This would help in their application in surface coating and metal ion reduction (Singh et al., 2018). These biofunctional groups provide stability and help in bonding the analyte and green nanoparticles in sensing applications.

4.3 X-Ray Diffraction (XRD)

Determining the crystalline structure of nanomaterials synthesized using environmentally friendly methods requires X-ray diffraction (XRD) measurements. The diffraction patterns show the nanocrystal size, degree of crystallinity, purity and crystal lattice planes.

Singh et al. (2018) found that nanometals and metal oxide nanogels made with environmentally friendly methods have unique diffraction peaks that are characteristic of the standard diffraction peaks of the crystalline structures. This helps to conclude that biosynthetic routes for nanomaterials do not adversely affect crystallinity (Singh et al., 2018). X-ray measurement of the crystal size can be used to determine the average crystal size with the Scherrer equation.

4.4 Electron Microscopy Techniques

Scanning electron microscopy (SEM) produces images of a sample by scanning its surface with a beam of electrons. These electrons interact with the sample's atoms, producing various signals that provide information about the surface topography and composition with high resolution.

Transmission electron microscopy (TEM) is capable of providing diverse information at the nanometer and, ideally, atomic levels. It reveals not only the positions of atoms but also their types and how they are bonded together. For this reason, TEM is considered an essential tool in nanoscience, including in bio-nanomaterials and other fields. Environmentally friendly nanocrystals often exhibit spherical shapes with limited size distributions, according to a study by Abbas *et al.* (2025). Scanning electron microscopy provides additional data on surface roughness and particle agglomeration, particularly for nanomaterials containing metal oxides and carbon. Atomic force microscopy (AFM) has many advantages over other measurements, as it gives a three-dimensional picture of the sample's topography and crystal structure with greater accuracy.

4.5 Surface Area and Porosity Analysis

Specific surface area and porosity can influence analyte adsorption and the accessible active sites in sensing materials. Brunauer–Emmett–Teller (BET) gas adsorption can quantify specific surface area, while complementary characterization is needed to understand structure–property relationships (Mourdikoudis et al., 2018). A general claim that green routes always give higher surface areas than conventional routes is not supported without matched comparative measurements.

4.6 Integrated Structural Analysis

Through FTIR measurements, UV-Vis spectroscopy, X-ray patterns, and electron microscopy images, a characterization of the environmentally friendly nanomaterials is presented in Figure 4. Combining these methods provides a clear and comprehensive understanding of the surface composition and chemistry of these crystalline nanoparticles. If high electrical accuracy and electronic control are required, electrochemical sensing is preferred; if simplicity, speed, and a visible response are required, optical/colorimetric sensing is the way forward. The key point is that the nanomaterial itself can be the core of the system in both methods, but the physics through which the signal is read differs: sometimes via electrons, and sometimes via light.

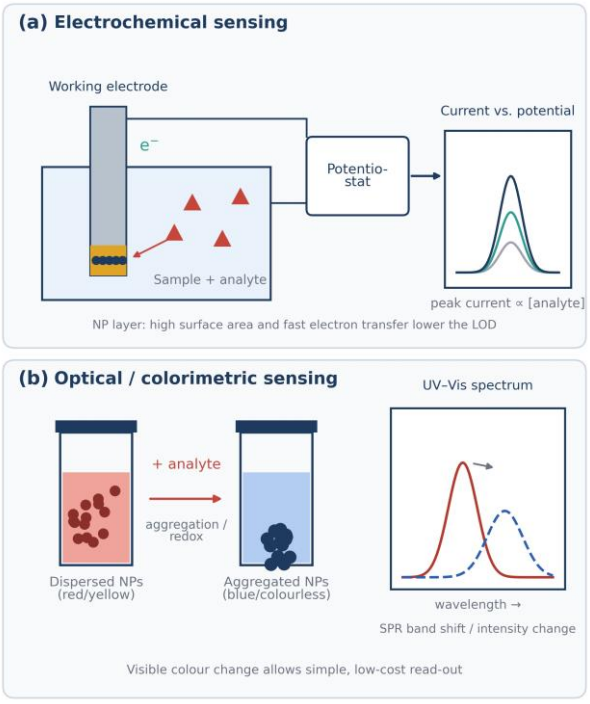


Figure 4: Application of green-synthesized nanomaterials in analytical sensing platforms, including electrochemical and optical detection mechanisms: (a) electrochemical sensing at a nanoparticle-modified electrode and (b) colorimetric sensing based on nanoparticle aggregation and a shift of the surface plasmon resonance band.

Methods for preparing nanomaterials from environmentally friendly materials provide nanomaterials with distinctive properties that are homogeneously reproducible and suitable for high-performance analytical sensing applications, as this integrated characterization demonstrates.

5. Analytical Applications and Sensing Performance of Green-Synthesized Nanomaterials

Nanomaterials prepared using environmentally friendly methods have shown outstanding performance in electrochemical, optical, and colorimetric sensing processes over the past ten years, due to the high surface area-to-volume ratio and improved surface chemical properties that these nanomaterials offer.

5.1 Electrochemical Sensing Applications

Sensitivity can be increased and detection limits lowered by strong interactions between environmentally friendly nanomaterials and the analytes being measured. This is because these nanomaterial electrochemical sensors have a larger effective surface area and better electron transport kinetics.

Üçdemir Pektaş *et al.* (2024) designed an amperometric glucose biosensor in which a carbon paste electrode was modified with silver nanoparticles synthesized from waste tea extract, with glucose oxidase immobilized by cross-linking. Glucose was determined through the reduction of hydrogen peroxide at +0.4 V versus Ag/AgCl, and the biosensor was applied to a commercial fruit juice sample, illustrating how green-synthesized nanoparticles can be integrated into practical electrochemical platforms.

Dodevska et al. (2021) reviewed the use of biosynthesized metallic nanoparticles in electrochemical sensors. Their review provides context for electrode modification strategies; it should not be interpreted as evidence for a specific plant-derived gold nanoparticle dopamine sensor.

Reviews of sustainable sensor materials describe promising electrochemical approaches for heavy-metal-ion detection, including green-derived carbon materials (Bilge et al., 2021). Their analytical performance depends on electrode composition, available active sites, transport characteristics and validation conditions; the present review does not claim a specific ZnO sensor result without a traceable primary study.

5.2 Optical and Colorimetric Sensing

The substances to be analyzed can be easily detected with the naked eye using the distinctive optical properties of environmentally friendly nanomaterials, which are highly advantageous for optical sensing systems, particularly colorimetric and fluorescent sensors. The strong surface plasmon resonance of metallic nanoparticles enables the detection of the target analytes.

Kumar *et al.* (2017) used environmentally friendly silver nanoparticles to create a colorimetric sensor for mercury ions. The nanoparticles were prepared from an aqueous leaf extract of *Murraya koenigii* under sunlight, and Hg^{2+} was detected through the change in their surface plasmon resonance band, with a linear response from 50 nM to 500 μM. An oxidation–reduction interaction between the nanoparticles and Hg^{2+} was proposed as the sensing mechanism. Ahmed *et al.* (2020) similarly reported silver nanoparticles prepared from the root extract of *Bistorta amplexicaulis* as a dual colorimetric sensor for Hg^{2+} and Pb^{2+}, with limits of detection of 8.0×10^{-7} M and 2.0×10^{-7} M, respectively.

Fluorescent carbon dots produced from natural raw materials have also been widely used in sensing applications. Liu *et al.* (2020) demonstrated that carbon dots made from biomass waste using environmentally friendly methods showed high sensitivity to metal ions and proteins, as well as strong photoluminescence.

5.3 Biosensing and Biomedical Analysis

Environmentally friendly nanomaterials can be used in biosensing applications. Their low toxicity and biocompatibility make them particularly valuable, and these properties are essential for analytical applications, both *in vitro* and *in vivo*. A study by Chang *et al.* (2019) demonstrated the successful integration of bio-modified gold nanoparticles, produced using environmentally friendly methods, into electrochemical sensors for protein detection. The

exceptional stability and selectivity of these devices are attributed to their biomolecule-rich surface.

5.4 Environmental and Food Analysis

Environmental water pollution monitoring is one of the most active applications of environmentally friendly nanomaterials. These materials have been efficiently used as the basis for electrochemical and optical sensors for detecting heavy metals, organic dyes, and pesticides.

Akash et al., 2021, have designed a pesticide sensor combined with an environmentally friendly copper oxide (Cu2O) nanobeads from contaminated water samples. The device's high sensitivity and repeatability were demonstrated, presenting a promising avenue for using the technology to analyze real-world samples while being environmentally friendly.

5.5 Comparative Sensing Performance

It has been demonstrated that nanomaterials with environmentally friendly methods of preparation can be as effective or even more effective than the nanomaterials with conventional methods of preparation. These advances are mainly due to better dispersion, fewer surface defects, a more biochemically active surface composition and higher surface area and crystalline volume.

Singh et al. (2018) provided a review on green synthesized metal and metal oxide nanoparticles application in environment and pointed out certain technical challenges in the development of green nanomaterials.

Representative analytical performance data from sensors based on green-synthesized nanomaterials for the target analytes, techniques and reported detection limits (LOD) or linear dynamic ranges (LDR) are summarized in Table 2.

Table 2: Representative analytical performance of sensors based on green-synthesized nanomaterials.

Nanomaterial (source)	Target	Technique	Reported performance	Ref.
Murraya koenigii AgNPs	Hg^{2+}	Colorimetric (SPR band)	LDR 50 nM–500 μM	Kumar et al., 2017
Bistorta amplexicaulis AgNPs	Hg^{2+}	Colorimetric	LOD 8.0×10^{-7} M; LDR 1×10^{-7}–1×10^{-6} M	Ahmed et al., 2020
Bistorta amplexicaulis AgNPs	Pb^{2+}	Colorimetric	LOD 2.0×10^{-7} M; LDR 1×10^{-8}–1×10^{-6} M	Ahmed et al., 2020
Biologically synthesized, unmodified AgNPs	Hg^{2+}	Colorimetric (SPR, UV–Vis)	LOD 2.2×10^{-6} mol L^{-1}	Farhadi et al., 2012
Waste-tea AgNPs + glucose oxidase on carbon paste electrode	Glucose	Amperometry (+0.4 V vs. Ag/AgCl)	Applied to a commercial fruit juice sample	Üçdemir Pektaş et al., 2024

LOD, limit of detection; LDR, linear dynamic range; SPR, surface plasmon resonance.

6. Challenges, Limitations, and Future Perspectives

The difficulty of preparing and using environmentally friendly nanomaterials in an analytical way is one of the most important concerns that make their application more restricted to environmental pollution monitoring and commercialisation, and this is called Reproducibility.

Nanoparticle size, shape, and surface chemical composition can vary greatly from batch to batch, which can be caused by the variability of biological sources, extraction methods, and by seasonal effects. Singh et al. (2018) pointed out that this variability still presents a significant hurdle in developing an environmentally friendly nanomaterial, as well as in getting regulatory approval for it in the use of analytical instruments.

A major disadvantage is the lack in control of properties of nanoparticles such as size, selectivity etc. Although green preparation processes are environmentally friendly, obtaining uniform and consistent size distribution and shape control similar to chemical preparation is difficult. Khan et al. (2019) found that uncontrolled formation and growth processes can adversely affect sensor repro-ducibility and analysis accuracy.

Scalability is also a crucial factor to consider. Many techniques of green synthesis are not directly scalable to industry due to being optimized at the laboratory scale. Singh et al. (2018) have highlighted that yield and quality of the synthesized biological agents are less in the case of large scale synthesis, particularly in plant and microorganism based methods.

The further research needs of green-nanomaterial sensors include real-sample validation and long-term stability. Before the use of the test in complex samples, matrix effects and interference, recovery and repeatability should be tested (Dodevska et al., 2021; Bilge et al., 2021).

Future studies should concentrate on:

- Creating standardized procedures for synthesis;
- Clarifying molecular-level reaction processes;
- Combining portable sensing platforms and microfluidic systems with green-synthesised nanomaterials;
- Increasing use in on-site environmental monitoring and point-of-care diagnostics (Chiravoot et al., 2024).

Current limitations may be addressed by potential solutions offered by recent developments in hybrid green–chemical techniques and machine-learning-assisted synthesis optimization. According to Singh et al. (2018), performance and repeatability might be greatly improved by combining controlled post-functionalization with green synthesis.

All things considered, overcoming these obstacles will be essential to converting green-synthesised nanomaterials from scholarly studies into practical analytical tools.

7. Conclusions

Green synthesis of nanomaterials has become a potent and sustainable strategy that unites green chemistry and nanotechnology. Environmentally safe methods that reduce harmful chemicals and produce functionally rich nanomaterials have been created by employing biological resources such as plant extracts, microorganisms, and natural polymers.

Green-synthesized nanomaterials have shown great promise for analytical uses in this review, especially in electrochemical, optical, and colorimetric sensing. Analyte interaction, electron transport, and overall sensing performance are all improved by the presence of biofunctional surface groups, frequently matching or outperforming their conventionally synthesized counterparts.

Although the above stated properties of the nanomaterials produced by the aforesaid green techniques are significant, there are still some issues associated with their long-term stability, reproducibility and scalability. The solution of these problems will rely on standardisation of manufacturing processes, elucidation of their mechanism and strict analytical verification in the future.

It is important to have a regulatory and standardization path forward for these sensors to go beyond laboratory demonstrations. The terminology and characterization practices of ISO/TC 229 (Nanotechnologies) provide a convenient foundation for reporting the plant- and microbe-derived nanomaterials' size, surface chemistry and batch-to-batch variability in a similar manner. Developers have to also document the biological source (species, plant part, season and extraction solvent) as well as a phytochemical fingerprint of the extract, validate sensor performance in real matrices, following accepted analytical method validation requirements, and complete environmental, health and safety assessment in accordance with national and regional nanomaterial regulations prior to commercialization. However, there is still a need for interlaboratory comparisons, reference materials, and ISO technical specifications (ISO/TS) specifically for biogenic nanomaterials, and this should be a priority for future work.

In short, environmentally friendly nanomaterials offer a practical and eco-friendly framework for future analytical sensing technologies aimed at eliminating pollutants that pose a risk to both the environment and individuals. Further interdisciplinary research is expected to enhance their performance and facilitate their transition from laboratory research to practical applications.

Conflict of Interest

The authors declare no conflict of interest.

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