

Green Synthesis and Environmental Applications of Functionalized Nanomaterials

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Abstract

The fast growth in the field of nanotechnology has brought many new possibilities for solving environmental problems using highly advanced materials that have tunable physicochemical properties. But traditional techniques of preparation of nanoparticles involve poisonous reagents, toxic solvents, extreme temperatures, high energy costs, and production of environmentally unfriendly by-products. The green synthesis technique uses plants, microorganisms, biomolecules, agricultural wastes, and other renewable sources to prepare materials. Functionalization helps to increase the efficiency of nanomaterials by imparting certain chemical groups, surface sites, catalytic sites, and magnetic nature to nanomaterials. This research paper is a review of recent developments in the green synthesis and environmental applications of functionalized nanomaterials, especially plant-mediated nanoparticles, carbon-based nanomaterials, metal and metal oxide nanoparticles, magnetic nanomaterials, graphene-based nanomaterials, silica nanoparticles, and biomass-based nanocomposites. The uses of these materials in wastewater treatment, removal of heavy metals, decomposition of organic pollutants, antimicrobial treatment, environmental sensing, remediation of soil, and photocatalysis have been studied. The study adopted a systematic narrative review strategy to analyze the results of recent peer-reviewed articles, especially those published between 2020 and 2024. The results suggest that functionalization could be a highly effective tool for increasing surface area, adsorption capacity, selectivity, catalytic efficiency, dispersion, and recycling efficiency. Some tables highlighting the synthesis methods, types of materials, environmental applications, mechanisms of pollutant removal, and benefits of these materials show the increasing significance of green functionalized nanomaterials. However, issues related to nanoparticle aggregation, toxicity, reproducibility, recovery, scalability, high cost, stability, and life cycle are hindering their large-scale application. It is essential for future studies to consider green chemistry, biotechnology, artificial intelligence, circular economy, and life cycle assessment to design safe, multifunctional, recyclable, and scalable nanomaterials for environmental protection.

Keywords: Green synthesis; Functionalized nanomaterials; Nanotechnology; Environmental remediation; Wastewater treatment; Heavy-metal removal; Photocatalysis; Green nanotechnology.

INTRODUCTION

The problem of environmental pollution has now become one of the most significant problems caused by fast-paced industrialization, urbanization, intensive farming, mining, transport activities, and increased exploitation of natural resources. Water, soil, and air are constantly subjected to such

harmful substances as heavy metals, dyes, pharmaceuticals, pesticides, hydrocarbons, pathogens, nutrients, volatile organic compounds, and other emerging pollutants. Some of them are non-biodegradable, toxic, persistent, or prone to bioaccumulation. As a result, conventional treatment technologies find it more and more challenging to achieve effective purification at low concentrations in economically and environmentally sustainable ways. Nanotechnology is a promising technological approach to the problem of environmental purification since nanomaterials have unique surface, optical, electrical, magnetic, catalytic, and chemical properties. Being extremely small, they provide high surface-to-volume ratio and many active surface sites. They can be used for adsorption, catalysis, photocatalysis, membrane separation, sensing, disinfection, and pollutants transformation. According to recent reviews, the nanomaterials designed for the problem of heavy metal removal are especially perspective due to their surface chemistry, porosity, charge, and functional groups that can be adjusted.

In spite of the technology behind it, the conventional method of producing nanomaterials can lead to environmental challenges. The physical and chemical methods used in the production of nanomaterials need the use of highly effective reducing agents, organic solvents, toxic stabilizers, high pressure and high temperature. Such residual chemicals will be attached to the produced nanoparticles, and might even affect the behavior of the nanoparticles in the environment and in biology. This is why the idea of green nanotechnology was formed.

Green synthesis typically uses plant extracts, bacteria, fungi, algae, enzymes, proteins, polysaccharides, agricultural waste, and other biological systems. Plant-based substances such as phenolics, flavonoids, terpenoids, alkaloids, proteins, sugars, and organic acids have the ability to act as reducing, capping, and stabilizing agents. A major review study conducted in 2024 on green synthesis revealed that green synthesis can make use of microorganisms, fungi, plants, and agro-industrial biowaste. (DOI) Besides nanoparticle synthesis, an important advancement in green synthesis is that of surface functionalization. Surface functionalization refers to the introduction of certain chemical groups or secondary molecules on the surface of a nanomaterial for changing its physicochemical and environmental characteristics. Hydroxyl (–OH), carboxyl (–COOH), amino (–NH₂), thiol (–SH), sulfonate, phosphate, and other ligand functional groups can increase the binding sites and change the surface charge. Therefore, surface functionalization can aid in heavy metal and organic pollutants adsorption, catalysis, selective detection, dispersion, and environmental matrix compatibility.

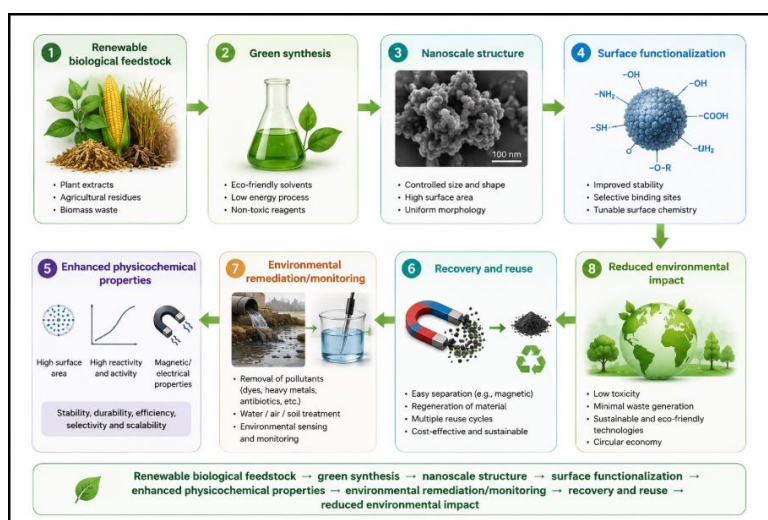
Functionalized nanomaterials are particularly suited for removal of heavy metals. Lead, cadmium, chromium, mercury, arsenic, copper, and nickel are examples of heavy metals which are not biodegradable. Functional groups on graphene oxide, silica, carbon, iron oxide, titanium dioxide, polymers and other types of nanomaterials can bind metal ions using electrostatic interactions, complexation, chelation, ion exchange and surface precipitation. A review dedicated to the role of functionalization in nanomaterials reported that functionalization determines adsorption ability, surface area, selectivity, and reusability. The green functionalized nanomaterials have various applications in the area of degradation of organic pollutants. Nanoparticles of metal and metal oxides synthesized using plants can act as photocatalyst and catalytic materials in the degradation of dyes, pesticides, pharmaceuticals and other persistent organic pollutants. Recent studies stress the synthesis

of plant-based nanoparticles through relatively simple processes and their use in wastewater treatment. Another emerging application of functionalized nanomaterials is environmental sensing. Functionalized nanomaterials have high surface areas and ligands which are able to detect specific analytes can be introduced. Nanoparticles of metals, carbon nanomaterials, quantum dots, polymers, dendrimers and metal-organic frameworks have been used for detection of heavy metals, pesticides, volatile organic compounds, toxic gases, industrial pollutants and pathogens.

BACKGROUND / CONCEPTUAL FRAMEWORK

Green synthesis and functionalization can both be seen as two inter-related stages of nanomaterials sustainability. The former dictates how the nanomaterial will be synthesized, whereas the latter determines how the surface of the material will behave after it is synthesized.

- The green synthesis method. Biological matter can be used as reducing and stabilizing agents, substituting dangerous chemical compounds. Plant matter is especially appealing since it is cheap and easy to obtain and has wide chemical diversity. Another way is microbial synthesis; however, the maintenance of biological conditions becomes more difficult in this case. Agricultural and food production waste becomes another circular economy method, as biomass waste can become a source of reducing substances or carbon sources.
- Nanomaterials can be produced as nanoparticles, nanorods, nanotubes, nanosheets, porous structures, quantum dots, nanofibers, or nanocomposites. Morphology affects their surface area, absorption capacity, catalytic ability, optical properties, and mobility.
- Functioning groups are added during synthesis itself or post synthesis via functionalization. They serve as binding groups, increase hydrophilicity, change surface charges, help with dispersion, or catalyze and sense.
- Functionalized nanomaterials can be involved in processes such as adsorption, photocatalysis, reduction, oxidation, membrane separation, anti-microbial activity, environmental sensing, and soil remediation. The conceptual pathway may therefore be expressed as:



The importance of this framework lies in the fact that sustainability cannot be measured on the basis of particle performance alone. The nanoparticle could be very efficient in terms of adsorption but would not be suitable if it uses toxic substances for synthesis, is non-recyclable, or produces particles in the environment.

It is, therefore, necessary to consider the whole lifecycle of the nanoparticle. Recent literature highlights the same point, and suggests that green nanomaterials are a combination of green chemistry and nanotechnology.

LITERATURE REVIEW

Green Synthesis of Nanomaterials

Green synthesis has emerged as an important strategy to produce nanoparticles in comparison to the traditional methods of nanoparticle production. Among the biological systems, plant extracts have been studied extensively. Phytochemicals present in leaves, fruits, seeds, roots, flowers, bark, peels, and agricultural waste have the ability to reduce metal ions and stabilize the formed nanoparticles. In general, the mechanism for green synthesis involves reduction of metal ions, followed by nucleation and growth. There is the possibility of biological molecules adsorbing on the nanoparticle surface in the form of a capping agent. This means that the biological extract would influence the size, morphology, stability, and surface chemistry of nanoparticles. Osman et al. reviewed green synthesis of nanoparticles and mentioned the use of plants, microorganisms, fungi, and agro-industrial biowaste in the process. The review was focused on environmental remediation and applications apart from the possible reductions in energy consumption and production cost compared to some conventional methods. (DOI) A 2024 review of plant-mediated metal nanoparticles mentioned the importance of plant-based materials in sustainable nanoparticle synthesis and wastewater treatment.

Functionalization of Nanomaterials

Functionalization is concerned with intentional alteration of the surface of a nanomaterial in order to impart specific chemical or physical properties. Covalent modification, adsorption, polymer coating, ligand immobilization, doping, compositing, and biomolecular immobilization are some techniques for doing so. The importance of functional groups lies in their contribution to adsorption-based environmental remediation. Amino groups are capable of coordination of metal ions, thiol groups are highly reactive towards several soft metal ions, whereas carboxyl and hydroxyl groups help in electrostatic attraction and complexation. Graphene oxide is a functionalized material with oxygen-containing groups and it can be further functionalized with polymers, amines, thiols, magnetic materials, and ligands. Similarly, functionalized silica has the ability to control surface chemistry owing to the presence of modifiable silanol groups.

Heavy-Metal Removal

Remediation of heavy-metal pollution is one of the most vital areas in nanomaterials-mediated remediation. Heavy metals, including lead, cadmium, chromium, mercury, arsenic, copper, and nickel, can come from activities such as mining, electroplating, batteries, metal processing, pigments, fertilizers, and industrial wastewater. Some nanoscale adsorbents which have shown high potential in

adsorbing heavy metals include graphene oxide, carbon nanotubes, layered double hydroxides, MXenes, metal–organic frameworks, zeolites, polymers, chitosan, and metal oxides. As reported in a 2024 state-of-the-art review, LDHs, graphene, CNTs, MXenes, MOFs, and ZIFs were considered to be promising nanostructured adsorbents in removing heavy metals. Functionally modifying the adsorbent enhances its efficacy due to creating extra binding sites. Possible mechanisms include electrostatic interactions, ion exchange, complex formation, chelation, surface precipitation, and redox reactions.

Organic Pollutant Degradation

Organic pollutants consist of dyes, pesticides, medicines, phenols, endocrine disruptors, and organic substances from industry. Adsorption could be used for removal of such pollutants from the water medium, and chemical transformations can be achieved using photocatalysis and catalytic reduction. Green synthesized metal oxide nanoparticles like TiO₂, ZnO, Fe₂O₃ and their composites have been studied for degradation using photocatalysis. Plant derived substances can take part in formation of nanoparticles and affect surface properties. Photocatalysis involves photon absorption, generation of electron-hole pairs, charge separation, and reactive oxygen species generation.

Carbon-Based Functionalized Nanomaterials

Carbon based nanomaterials consist of graphene oxide, reduced graphene oxide, carbon nanotubes, carbon dots, biochar based nanomaterials, and carbon nanocomposites of activated carbon. Their high surface area along with controllable surface chemistry makes them potential candidates for adsorption and sensing.

One of the most promising carbon nanomaterials is carbon dots owing to their photoluminescence and functional surface groups. Green synthesis from biomass and food wastes can make these nanomaterials environmentally friendly. Recent research on green carbon dot nanocomposites highlights their multifunctional nature and increasing environmental applications.

Magnetic Functionalized Nanomaterials

Nanoparticles with magnetic properties, especially those based on iron oxides, can offer a solution to the problem of retrieval. Once the pollutants have been adsorbed, the application of an external magnetic force will be able to separate the nanomaterials from the water. This means that magnetic functionalization can be used to achieve both effective adsorption and easy separation. The key benefit of this approach is the ability to recycle the nanomaterials.

Environmental Sensing

The use of functionalized nanomaterials in environmental sensors is becoming widespread. The high surface area of these materials enables interaction with minute amounts of analyte molecules, and their physical and chemical properties give rise to detectable responses. The scientific literature highlights that functionalized metal and metal oxide nanoparticles, quantum dots, carbon nanomaterials, polymers, dendrimers, and MOFs are potential materials for detection of heavy metals,

pesticides, toxic gases, volatile organic compounds, pathogens, and industrial pollutants. The reason why functionalization enhances selectivity of the system is the molecular recognition.

RESEARCH METHODOLOGY

This study adopts a systematic narrative literature review approach to examine the green synthesis and environmental applications of functionalized nanomaterials. This research draws on secondary sources from scientific literature and is not intended to provide laboratory-generated results for the first time. Sources of literature were found in scientific databases and main publishing houses. Keywords for literature search were combinations of such keywords as “green synthesis,” “functionalized nanomaterials,” “green nanoparticles,” “plant-mediated nanoparticles,” “biogenic nanomaterials,” “wastewater treatment,” “heavy metal removal,” “photocatalytic degradation,” “environmental sensing,” “biomass-derived nanomaterials,” and “nanoremediation.” More weight was given to the latest peer-reviewed articles and reviews in this field from 2020 to 2024, but at times some older, basic studies had to be cited to explain fundamental concepts. The literature was sorted out according to the following six analytical themes: (1) methods of green synthesis; (2) functionalization approaches; (3) heavy metal removal; (4) organic pollutant degradation; (5) environmental sensing; (6) recovery/recyclability/sustainability.

The selected papers were analyzed comparatively in terms of nanomaterial types, synthesis sources, functional groups, pollutants of interest, application to the environment, dominant removal mechanisms, recoverability, and limitations. As the studies under review utilize different experimental parameters such as different pollutant concentrations, catalyst doses, pH levels, reaction times, and analysis methods, statistical meta-analysis was deemed not to be appropriate. A comparative synthesis has been performed instead. Thus, the results tables provided below present literature-based comparative synthesis, but not experimental measurements. This point should be emphasized because of the methodological accuracy. Specific attention was paid to the possibility of satisfying the major criteria of sustainable environmental technology by a particular nanomaterial.

RESULTS / FINDINGS

This paper indicates that there is a trend toward combining green synthesis and functionalization in order to improve the environmental performance of nanomaterials. There are six comparative tables of the key results obtained.

Table 1. Green Synthesis Approaches for Functionalized Nanomaterials

Green synthesis approach	Major biological source	Typical nanomaterials	Important functional contribution	Environmental relevance
Plant-mediated synthesis	Leaves, fruits, roots, peels, seeds	Ag, Au, ZnO, Fe ₃ O ₄ , CuO	Phytochemical capping	Water treatment, photocatalysis

Microbial synthesis	Bacteria, fungi, algae	Ag, Au, Se, Fe-based NPs	Biomolecular stabilization	Bioremediation
Agricultural-waste synthesis	Rice husk, fruit peels, straw	Carbon, silica, metal composites	Renewable carbon/silica surface	Adsorption
Biomolecule-assisted synthesis	Proteins, enzymes, polysaccharides	Metal and metal-oxide NPs	Biocompatible surface groups	Sensing, remediation
Biochar-derived synthesis	Biomass residues	Functionalized carbon composites	Porosity and oxygen groups	Heavy-metal adsorption
Green hydrothermal/solvothermal routes	Water/benign solvents + biomass	Oxides, carbon dots	Controlled morphology	Photocatalysis

Green synthesis can be carried out using various types of renewable and biological sources, as indicated in Table 1 below. Plant-based synthesis is a good method to adopt since it involves the supply of both the reducing and stabilizing agents through the plants. Another aspect of sustainability brought about by agricultural waste is the transformation of the waste biomass to useful materials. Microbial and biomolecule-based methods offer specificity in the surface chemistry but need more process control.

Table 2. Major Functionalized Nanomaterials and Environmental Applications

Nanomaterial	Common functionalization	Major application	Principal mechanism
Graphene oxide	–COOH, –OH, –NH ₂ , polymers	Heavy metals, dyes	Adsorption/complexation
Fe ₃ O ₄ nanoparticles	Silica, chitosan, amines	Heavy metals, dyes	Adsorption + magnetic separation
TiO ₂	Metals, carbon, N-doping	Organic pollutants	Photocatalytic degradation
ZnO	Biomolecules, carbon, dopants	Dyes, pharmaceuticals	Photocatalysis

Silica nanoparticles	Amino, thiol, carboxyl groups	Metal ions	Complexation/adsorption
Carbon dots	N/S/O functional groups	Sensing, photocatalysis	Fluorescence/electron transfer
Chitosan nanocomposites	Amino/hydroxyl groups	Metals, dyes	Chelation/adsorption
MOF-based nanomaterials	Organic ligands/functional groups	Metals, organics, gases	Adsorption/catalysis

The findings show that functionalization helps to increase the environmental applications of nanomaterials. Carbonaceous materials offer a range of surfaces to work on, while magnetic iron oxide nanoparticles provide the advantage of being reusable. Metal oxides are useful where photocatalysis is considered. Silica and chitosan help to obtain a great number of binding sites for metal ions. This finding is confirmed by literature review where graphene, carbon, silica, titanium dioxide, and iron oxides are considered.

Table 3. Functionalized Nanomaterials for Heavy-Metal Removal

Target pollutant	Suitable functional groups/materials	Major removal mechanism	Important controlling factor
Pb ²⁺	–NH ₂ , –COOH, –SH, graphene oxide	Complexation/chelation	pH
Cd ²⁺	–COOH, –OH, –NH ₂	Surface complexation	Competing ions
Cr(VI)	Amine groups, Fe-based NPs	Adsorption/redox	pH and redox conditions
Hg ²⁺	–SH, sulfur-containing groups	Strong complexation	Functional-group density
As species	Fe oxides, amino groups	Adsorption/complexation	pH and speciation
Cu ²⁺	–COOH, –NH ₂ , chitosan	Chelation/ion exchange	Initial concentration
Ni ²⁺	Amino/carboxyl groups	Complexation/ion exchange	Ionic strength

Table 3 shows the significance of functional group selection based on contaminant chemistry. Sulfur-containing functional groups are especially valuable for bonding of some metal ions while amino and carboxyl functional groups are very flexible due to coordination and electrostatic interactions. Iron-containing nanomaterials can also be used in redox reactions for removal of some contaminants. The

performance of removal process depends heavily on pH as protonation/deprotonation affects the charge of the surface and the ability to bind pollutants. Modern literature reviews prove that pH, temperature, contact time, initial concentration, dosage of adsorbent and ionic strength are the key parameters of such removal process.

Table 4. Environmental Applications in Organic-Pollutant Removal

Pollutant category	Nanomaterial type	Functional role	Main process
Synthetic dyes	ZnO, TiO ₂ , graphene composites	Improved adsorption/light response	Photocatalysis
Pharmaceuticals	TiO ₂ , Fe ₃ O ₄ composites	Surface adsorption + reactive species	Photocatalysis
Pesticides	Metal oxides, carbon nanomaterials	Adsorption/catalytic activation	Catalysis
Phenolic compounds	Carbon/metal composites	Increased surface interaction	Adsorption/oxidation
Antibiotics	Graphene, ZnO, TiO ₂	Adsorption and degradation	Photocatalysis
Petroleum-derived pollutants	Iron/carbon nanocomposites	Redox/adsorption	Catalytic remediation

Evidence has been shown to suggest that functionalization may increase the effectiveness of treatment of organic pollutants through both adsorption and catalytic or photocatalytic conversion of the pollutants. This is because adsorption ensures accumulation of the pollutants at the sites where conversion occurs, whereas photocatalysis will allow for the chemical breakdown of the pollutants. This process may be better than simply using adsorption since the degradation process will reduce the need for disposal of the adsorbing material.

Table 5. Comparative Environmental Performance

Criterion	Conventional nanomaterial	Green-synthesized material	Functionalized green nanomaterial
Surface activity	High	High	Very high potential
Selectivity	Moderate	Variable	Generally improved
Adsorption capacity	Moderate–high	High potential	High–very high potential

Recovery	Often limited	Variable	Can be enhanced
Reusability	Moderate	Variable	Often improved through immobilization/magnetization
Toxic synthesis chemicals	Possible	Reduced	Potentially reduced
Renewable feedstock	Usually limited	High potential	High potential
Environmental compatibility	Material-dependent	Generally improved	Requires full assessment
Large-scale production	Established for some	Still developing	More complex

Such a comparison proves that functionalized green nanomaterials are especially appealing from the point of view of environmental and technological characteristics. The key strength of these materials is not their superiority to all conventional nanomaterials in terms of absolute catalytic or adsorption capabilities, but the possibility to unite high activity on the one hand with environmentally friendly production on the other. Still, functionalization may complicate and raise the cost of synthesis. Therefore, the optimal material would differ for different applications.

Table 6. Advantages and Limitations of Major Functionalized Nanomaterial Systems

Material system	Major advantages	Main limitations	Reuse potential
Functionalized graphene	High surface area, versatile chemistry	Difficult separation, possible toxicity	Moderate
Magnetic Fe ₃ O ₄ composites	Easy magnetic recovery	Aggregation/oxidation	High
Functionalized silica	Stable and tunable surface	Additional functionalization steps	High
TiO ₂ composites	Photostable, photocatalytic	Limited visible-light absorption in unmodified form	High
ZnO composites	Strong photocatalytic activity	Stability concerns under some conditions	Moderate–high

Chitosan nanocomposites	Biodegradable, abundant functional groups	pH sensitivity	Moderate
Carbon dots	Optical properties, low-dimensional structure	Scale-up and standardization	Application-dependent
MOF-based materials	Very high porosity and tunability	Stability and cost concerns	Potentially high

It is clear from Table 6 that no one nanomaterial meets all the environmental requirements. The magnetic materials show high recoverability, carbon materials give versatility in adsorption chemistry, metal oxides give the ability of photocatalysis, while biopolymer systems give re-newability and biodegradability features. Therefore, hybrid nanocomposites become more popular as these can integrate complementary properties. However, environmental safety of each material has to be considered before any practical application.

DISCUSSION

In terms of the findings, it is clear that the combination of green synthesis and functionalization can be considered a breakthrough in sustainable nanotechnology. Green synthesis helps to resolve the problem of the environmental impact of the process of nanoparticles creation, while functionalization enhances the properties of the synthesized nanomaterials. Thus, the combination of these methods can result in the development of environmental technologies that will be effective and sustainable. The first conclusion that can be made about the issue of environmentally oriented nanotechnology is that the surface chemistry plays a key role. Nanomaterials have high surface areas, but it does not mean that surface area determines their pollutant removal capacity. This is the reason behind functionalized materials having better performance than their non-functionalized counterparts. The second point refers to pollutant specific design. Contaminants in the environment are quite different in terms of chemical makeup and charge. Functional groups which bind with lead tightly may not work effectively with arsenic or chromium. Therefore, future designs of nanomaterials should focus on matching the chemical properties of pollutants and functional groups at the molecular level. The third point relates to greener synthesis of nanomaterials. Plant extracts and biomass waste serve as sources of renewable raw materials and can minimize the need for reducing agents. Moreover, agricultural waste can be used as starting material for producing carbon based or silica based nanomaterials. This way waste products could be turned into materials for environmental clean-up. Reviews in 2024 highlight plant biomass as potential source for nanomaterials.

The fourth one is the question of recovery and recyclability. Dispersed nanoparticles added directly into water become hard to recover after purification. There are economic and environmental problems. It would be convenient to use the magnetic functionalization, as the external magnetic field will help to recover the material. Another option is immobilization on the membranes, supports, beads, or any other porous materials. The fifth problem is connected with the photocatalytic conversion. Adsorption purifies the water from pollutants but only shifts them to other phase.

Photocatalysis provides the ability to convert them to smaller and less dangerous molecules. But the complete mineralization should be proved as the disappearing of parent compound does not mean full detoxification. It is not necessarily true that the use of the green approach in the process will result in nanoparticles which are environmentally friendly in the end. Particle size, surface modification, dissolving property, aggregating property, movement ability, and organism interaction are factors which may affect the toxicity. The current research findings in relation to biomass-based nanomaterials have highlighted these issues clearly. Plant extracts differ depending on species, geographical location, time of harvest, age of plant, extraction solvent, temperature, and storage conditions. These factors may have an effect on particle size and surface properties. Thus, the use of reproducible green synthesis methods is possible only when a standardized procedure for their preparation and characterization is followed. Moreover, a growing number of multifunctional nanocomposites has been reported in literature. One material may perform functions such as adsorption, photodegradation, antibacterial action, magnetic isolation, and even sensing. This will lead to a decrease in the number of stages of the process.

Future Perspectives

Future research should concentrate on designing multifunctional nanomaterials, which will allow for the high efficiency of remediation processes to be combined with the safe production of materials, selectivity to pollutants, ease of recovery, and good stability. It is promising to consider the combination of materials obtained from biomass and functionalization. For example, agricultural waste can serve as a renewable source of carbon, silica, cellulose, or lignin precursors, while functional groups required for the selective capture of particular pollutants can be incorporated into materials. Artificial intelligence and machine learning algorithms can facilitate the discovery of novel nanomaterials since they can predict the relationships between the process of synthesis, surface chemistry of materials, and their environmental properties. Future research should also pay more attention to the analysis of the life cycle, toxicity tests, and field trials. The material is regarded as environmentally sustainable only if its entire life cycle shows some environmental benefits. Hybrid materials capable of magnetophotocatalysis and adsorption-catalysis can become increasingly relevant.

CONCLUSION

Green synthesis and functionalization constitute two separate approaches to fabrication of environmentally friendly nanomaterials. Green synthesis may minimize the use of toxic substances and expensive procedures through the use of plants, microorganisms, biomolecules, agricultural waste products, and other renewable materials. In turn, functionalization allows for controlling the chemistry of surfaces and improving their properties with respect to adsorption, catalysis, selectivity, sensing, dispersion, and recycling. As shown by the studies reviewed in this paper, there are numerous applications of functionalized nanomaterials in wastewater purification, heavy metal removal, decomposition of organic contaminants, photocatalysis, environmental sensing, antibacterial action, and soil remediation. Functionalized graphene, silica, iron oxide, titanium dioxide, zinc oxide, chitosan, carbon dots, and MOF materials possess various adsorption, catalytic, optical, magnetic, and chemical properties. These comparative results have proven that the process of functionalization plays a crucial role in the cleanup of heavy metals since surface groups such as amino, carboxyl,

hydroxyl, and thiol groups may serve as selective binding sites. The functionalization process also makes possible the use of magnetic functionalization for separation and recycling. Photocatalytic functionalization allows combining the processes of pollutants' adsorption and chemical degradation to reduce the amount of secondary waste. However, the overall environmental impact of nanomaterials has to be analyzed in detail. Although green synthesis is an environmentally friendly way of producing nanomaterials, it does not always guarantee environmental safety.

REFERENCES

- [1] Osman, A. I., Zhang, Y., Farghali, M., et al. (2024). Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. *Environmental Chemistry Letters*, 22, 841–887.
- [2] Karnwal, A., & Malik, T. M. (2024). Nano-revolution in heavy metal removal: Engineered nanomaterials for cleaner water. *Frontiers in Environmental Science*, 12, 1393694.
- [3] Bhushan, D., Shoran, S., Kumar, R., & Gupta, R. (2024). Plant biomass-based nanoparticles for remediation of contaminants from water ecosystems: Recent trends, challenges, and future perspectives. *Chemosphere*, 365, 143340.
- [4] Siddeeg, S. M., Tahoona, M. A., Alsaiari, N. S., Shabbir, M., & Rebah, F. B. (2020). Application of functionalized nanomaterials as effective adsorbents for the removal of heavy metals from wastewater: A review. *Current Analytical Chemistry*, 17(1).

- [5] Feisal, N. A. S., Kamaludin, N. H., Ahmad, M. A., & Tengku Ibrahim, T. N. B. (2024). A comprehensive review of nanomaterials for efficient heavy metal ions removal in water treatment. *Journal of Water Process Engineering*, 64, 105566.
- [6] Recent advances of plant-mediated metal nanoparticles: Synthesis, properties, and emerging applications for wastewater treatment. (2024). *Journal of Environmental Chemical Engineering*, 12, 112345.
- [7] Dave, R., Pandey, K., Jain, S., Kshtriya, V., & Sengupta, P. (2024). Functionalized nanomaterials for detecting environmental pollutants. *ChemistrySelect*, 9, e202402477.
- [8] Emerging directions in green nanomaterials: Synthesis, physicochemical properties and applications. (2024). *Materials Today Communications*, 40, 109335.
- [9] Green synthesis and multifaceted applications: Challenges and innovations in carbon dot nanocomposites. (2024). *Discover Nano*, 19, 205.
- [10] Metal oxide nanoparticles' green synthesis by plants: Prospects in phyto- and bioremediation and photocatalytic degradation of organic pollutants. (2023). *Processes*, 11, 3356.
- [11] Singh, A., Tyagi, P., Ranjan, R., Sushkova, S. N., Minkina, T., Burachevskaya, M., & Rajput, V. D. (2023). Bioremediation of hazardous wastes using green synthesis of nanoparticles. *Processes*, 11, 141.
- [12] Exploring synthesis and applications of green nanoparticles and the role of nanotechnology in wastewater treatment. (2024). *Bioresource Technology Reports*.
- [13] Adsorptive removal of heavy metals from wastewater using emerging nanostructured materials: A state-of-the-art review. (2024). *Separation and Purification Technology*, 343, 127018.
- [14] Effects of environmental metal and metalloid pollutants on plants and human health: Exploring nano-remediation approach. (2024). *Stress Biology*.
- [15] Advancing nanomaterial synthesis: Harnessing green chemistry for sustainable innovation. (2024). *Green Analytical Chemistry*, 11, 100148.
- [16] Comparative analysis of chemical vs. green synthesis of nanoparticles and their various applications. (2024). *Environmental Nanotechnology, Monitoring & Management*, 22, 100988.
- [17] Plant-mediated green synthesis of nanomaterials for environmental remediation. (2023). Recent literature on plant-derived nanoparticles and pollutant degradation.
- [18] Functionalized carbon-based nanomaterials for environmental applications. (2024). Recent literature addressing adsorption, catalysis, sensing, and remediation.

- [19] Green nanotechnology for sustainable wastewater treatment. (2024). Recent literature addressing plant-mediated synthesis, adsorption, photocatalysis, and bioremediation.
- [20] Functional nanomaterials for environmental monitoring and remediation. (2024). Recent literature on pollutant detection, adsorption, catalytic transformation, and nanoremediation.