

Plant Based Nanomaterials for Sustainable Water Purification

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Abstract: *In addition to the benefits of recyclability and biologically informed building of specific nanomaterials, a number of avenues are available to enhance water treatment capabilities via plant sources. The aim of this paper is to critically review the plant-extract mediated iron and zinc oxide nanoparticles, cellulose nanofibers and carbon nanomaterials produced from biomass. A selected primary study was targeted and the outcome compared with regard to synthesis routes, contaminant-removal mechanisms, treatment performance and practical limitations. There are published applications that include: metal-ion capture, oil-water separation, nitrate removal, dye photodegradation, and chromium reduction. Reported removal percentages, however, are for different pollutants and operating conditions and are not applicable for ranking materials in general. Four requirements for credible claims concerning sustainability of feedstock processing, of testing of the water-matrix, of material recovery and of assessment of energy use and secondary waste are identified in the analysis. The use of immobilized composites and reusable membranes offers practical solutions to keep active nanomaterials in place but still need to look into the mechanical stability and longevity of these solutions. Environmental safeguards and reduction of life-cycle impacts are not determined by plant origin. Future studies should be conducted to compare the performance of full treatment systems with contaminant mass balances, residual-particle, regeneration data and cost per volume of compliant water produced. The review indicates plant-based nanomaterials have the potential to be used as elements of integrated water-treatment systems, but their use will rely on the demonstrated performance and environmental advantages.*

Keywords: *plant-mediated synthesis; nanocellulose; carbon dots; photocatalysis; adsorption; wastewater treatment; sustainability.*

I. INTRODUCTION

Technologies used in water purification must be able to tackle dissolved chemicals, suspended material, and biological contamination; reduce energy usage and secondary waste. While conventional treatment processes continue to be necessary, there are some applications that still call for more selective sorbents and additional polishing processes. The use of nanomaterials is of interest because the surface chemistry, dimensions of the particles, and pore structure can be modified to change the interaction between contaminants and the material. These properties are only useful if the active material is accessible, stable, recoverable, during operation.

Different origins of materials can be termed plant-based nanomaterials. In plant-mediated synthesis, an extract is used to aid the preparation or stabilization of an inorganic nanoparticle but the resulting material is still predominantly comprised of metal or metal oxide. Plant matter provides the structural polymer or carbon precursor in biomass derived materials. Thus, the synthesized zinc oxide and cellulose nanofiber and carbon dots from the leaf extract are significantly different in their origin. This distinction is important because the requirements, degradation and potential environmental releases are influenced not only by the botanical source but also the final product.

In early investigations, it was identified that cellulose membrane and sorption functions were useful; later, plant-assisted photocatalysts and carbon composites (Ma et al., 2011; Ma et al., 2012; Mousa et al., 2024; Sharma et al., 2025) were added to the list. Routes should be evaluated according to their purpose of treatment. There are various outcomes that can be measured in terms of a membrane rejection ratio, an adsorption capacity or a photochemical concentration decrease. It would be improper to use them to create a single performance score, without similar conditions.

This paper explores the link between material source, extraction process and ecological aspects. It offers a framework to evaluate the success of laboratory processes that differentiates a successful laboratory removal from a sustainable claim of clean water purification.

II. RESEARCH OBJECTIVES

The aims of the study were:

- To classify the principal types of plant-based nanomaterials and their synthesis routes for water treatment.
- To examine contaminant-removal mechanisms and treatment performance reported in selected published studies.
- To identify the operational limitations and environmental concerns associated with these materials.
- To develop practical criteria for evaluating future experimental studies and sustainable water-treatment systems.

III. LITERATURE REVIEW

Nasrollahzadeh et al. (2020)¹ discussed the progress of green synthesized nanocatalysts and nanomaterials for water treatment and highlighted the applications of biological methods as alternative to conventional chemical and physical methods of synthesis. The study showed that plant-derived materials and other biological resources may be used as reducing, stabilizing and capping agents in the process of nanoparticle formation and thus lower the need for hazardous chemicals and energy intensive processes. High surface area, chemical reactivity and catalytic activity were reported for green-synthesized nanomaterials which are suitable for heavy metal removal, dye removal and removal of other aqueous contaminants. The authors also pointed out that recovery, regeneration, toxicity, and biosafety should be considered prior to the large-scale application. This study proves that sustainability can't be judged only in the synthesis phase of treatment and covers the treatment process completely in order to recover nanoparticles as well as environmental risks.

Magalhães-Ghiotto et al. (2021)² reviewed the use of green nanoparticles in the treatment of water, focusing on their efficiency as removers, their ability to be regenerated, their environmental toxicity and the possibility of their large-scale production. The authors indicated that plant mediated nanoparticle synthesis has gained more attention due to the plant extracts containing naturally occurring compounds which act as reducing and stabilizing agents. The utility of green nanoparticles in the treatment of various contaminants such as dyes, heavy metals and other pollutants have been investigated. The study revealed, however, that leaching of nanoparticles and potential toxicity to the environment are significant constraints. The authors also stated that very efficient laboratory materials cannot be deemed as sustainable without assessing their production, regeneration, disposal and environmental behavior. The findings are especially important for plant-based nanomaterials as the use of renewable plant resources can enhance the sustainability of synthesis and controlled recovery and reuse are needed to avoid secondary contamination.

¹ Nasrollahzadeh, M., Sajjadi, M., Iravani, S., & Varma, R. S. (2020). Green-synthesized nanocatalysts and nanomaterials for water treatment: Current challenges and future perspectives. *Journal of Hazardous Materials*, 401, 123401. <https://doi.org/10.1016/j.jhazmat.2020.123401> (PubMed Central (PMC))

² Magalhães-Ghiotto, G. A. V., de Oliveira, A. M., Natal, J. P. S., Bergamasco, R., Gomes, R. G., et al. (2021). Green nanoparticles in water treatment: A review of research trends, applications, environmental aspects and large-scale production. *Environmental Nanotechnology, Monitoring & Management*, 16, 100526. <https://doi.org/10.1016/j.enmm.2021.100526> (ScienceDirect)

Bognár et al. (2022)³ investigated sustainable green nanotechnologies for water purification and noted that the synthesis of functional nanomaterials is becoming popular with increasing use of renewable biological resources, especially plant extracts. The review was directed towards nanomaterials applied in the heterogeneous photocatalytic process and other advanced processes for water treatment, especially to semiconductor nanoparticles, which include TiO₂ and ZnO. The bioactive compounds found in plants can be used as reducing and stabilizing agents in the synthesis of nanoparticles and could be a greener alternative to traditional chemical synthesis methods. The authors highlighted the potential of photocatalytic nanomaterials for the degradation of persistent organic pollutants such as dyes, pharmaceuticals, and pesticides, under the right irradiation conditions. The study also acknowledged that the traditional approach to nanomaterial synthesis may involve hazardous chemicals, while the promising applications of nanotechnology in the treatment industry necessitate greater efficiency, reproducibility and effectiveness in nanomaterial synthesis that meets green nanotechnology requirements. Therefore, the plant-assisted synthesis is a significant path for more environmentally friendly photocatalytic water purification.

Nguyen et al. (2022)⁴ conducted a systematic review of the synthesis of nanoparticles using plants and their use in water treatment, which showed that plant phytochemicals like polyphenols, flavonoids, terpenoids, and other bioactive molecules could be involved in nanoparticle reduction and stabilization. The authors identified several nanoplasts, such as Ag, Au, Cu and CuO, ZnO, TiO₂, Fe₃O₄, and ZrO₂, and their capability to adsorb, catalyse degradation and remove various contaminants. Green nanoparticles were found to be highly active against synthetic dyes, antibiotic, heavy metals and oils with a high rate of removal of pollutants from many reported systems. Importantly, the review also revealed that synthesis conditions, plant composition, particle morphology, and surface chemistry significantly affects the treatment performance. The observations suggest that the use of plant biomass is not only a sustainable alternative to chemical reagents, but can also influence the physicochemical properties and functionality of the nanomaterials.

Bhushan et al. (2024)⁵ recently reviewed the use of plant-biomass-based nanoparticles for the remediation of contaminants in aquatic environments and highlighted their potential for the remediation of organic and inorganic pollutants, pharmaceuticals and other emerging contaminants. The review revealed that different parts of plants such as leaves, roots, flowers, stems, seeds, tubers and bark, when processed into nanoparticles, can be involved in contaminant removal processes and participate in surface interactions such as adsorption, reduction, photocatalytic degradation, complexation, ion exchange or other interactions. The authors concluded that the key factors influencing the practical performance of plant-based nanomaterials were pH, surface functional groups, particle size, stability, toxicity, cost of production and recyclability. In particular, the potential ecological issues of nanoparticles released to aquatic environments were considered. Future studies should, therefore, focus not only on reporting removal percentages, but also on the recovery, reuse, toxicity, stability and life-cycle sustainability of nanoparticles. The findings of this study offer a solid foundation to view plant biomass nanomaterials as a promising but still nascent technology for sustainable water purification.

IV. REVIEW METHODOLOGY

A focused narrative review was prepared via scholarly web-based search and available publisher/institution-based research record. Use plant-derived nanoparticles, nanocellulose membranes, biomass-derived carbon dots, and some terms related to water treatment: adsorption, photocatalysis, nitrate, chromium to search for expressions. A search and

³ Bognár, S., Putnik, P., & Šojić Merkulov, D. (2022). Sustainable green nanotechnologies for innovative purifications of water: Synthesis of the nanoparticles from renewable sources. *Nanomaterials*, 12(2), 263. <https://doi.org/10.3390/nano12020263> (PubMed Central (PMC))

⁴ Nguyen, N. T. T., Nguyen, L. M., Nguyen, T. T. T., Liew, R. K., Nguyen, D. T. C., & Tran, T. V. (2022). Recent advances on botanical biosynthesis of nanoparticles for catalytic, water treatment and agricultural applications: A review. *Science of the Total Environment*, 827, 154160. <https://doi.org/10.1016/j.scitotenv.2022.154160> (ScienceDirect)

⁵ 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. <https://doi.org/10.1016/j.chemosphere.2024.143340> (PubMed)

source verification was carried out on 7 October 2026. Only those studies published in the last 15 years (2011–2025) were selected to reflect basic studies and recent advances. This period is not an exhaustive period of literature, but rather a selected period of literature⁶.

All plant-feedstocks or plant-assisted synthesis had to have a direct link with a water-treatment use for inclusion. The primary studies with known publication information were given more weight. Records were excluded if they only addressed the production of nanoparticles or applications not related to the treatment. Plant polymers were separated from non-plant biopolymers and bulk biomass sorbents were not considered to be nanomaterials.

The evidence was sorted into feedstock, material identity, treatment mechanism, reported outcome, and practical qualification. Numerical values were only reproduced as source-specific literature values. No new experiments were performed, original statistical tests were not performed, and pooled effect size calculation was not done. This review was not conducted systematically nor as a meta-analysis, and it does not provide a count of the database screening or a PRISMA flow diagram. The evidence is incomplete and not comparable in terms of completeness and comparability due to selective retrieval, experimental differences, and in-access to some full-texts⁷.

Result:

Table 4.1: Publication-Year Distribution of the Seven Studies Cited in the Original Draft

Publication year	Number of cited studies
2011	1
2012	1
2013	1
2016	1
2024	2
2025	1
Total	7

Interpretation

Table 4.1 shows the year of publication of the seven studies referred to in the original draft. Studies published in 2011, 2012, 2013, 2016, and 2025 contributed one reference each, representing 14.29% per year. Two studies were added during the year 2024 (28.57% of the total number). This distribution shows the combination of foundational and more recent research on plant based nanomaterials in water purification. Previous investigations were reviewed, and new publications were cited in discussions regarding new material applications. These figures, however, represent the selected reference list only and do not provide an indication of the overall publication trend, growth of research or the comprehensiveness of the literature search⁸.

⁶ Mathew, S., & Mathew, B. (2023). A review on the synthesis, properties, and applications of biomass derived carbon dots. *Inorganic Chemistry Communications*, 156, 111223. <https://doi.org/10.1016/j.inoche.2023.111223> (ScienceDirect)

⁷ Gan, J., Chen, L., Chen, Z., Zhang, J., & Yu, W. (2023). Lignocellulosic biomass-based carbon dots: Synthesis processes, properties, and applications. *Small*, 19(48), 2304066. <https://doi.org/10.1002/sml.202304066> (Wiley Online Library)

⁸ Palacio-Vergara, M., Álvarez-Gómez, M., Gallego, J., & López, D. (2023). Biomass solvothermal treatment methodologies to obtain carbon quantum dots: A systematic review. *Talanta Open*, 8, 100244. <https://doi.org/10.1016/j.talo.2023.100244> (DOI)

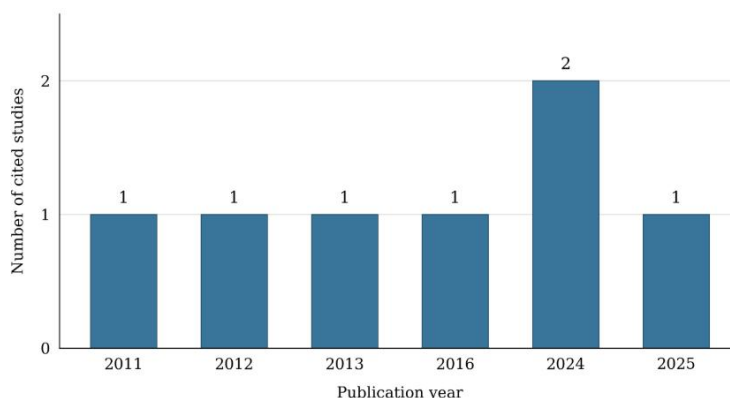


Figure 4.1: Publication-Year Distribution of the Seven Studies Cited in the Original Draft

V. MATERIAL CLASSES AND SYNTHESIS PRINCIPLES

Phenolic compounds, carbohydrates, organic acids, and other molecules that can interact with metal precursors can be present in plant extracts. They are different depending on the precursor chemistry and processing conditions. Reduction may be applicable to some metallic systems, however, in the preparation of metal-oxide, the term complexation, precipitation, stabilization, and then thermal conversion may be more suitable. If all extracts have the same role as a reducing-agent, this can give an incorrect impression about the chemistry. Structural and chemical characterization is needed to confirm material identity⁹.

Nanocellulose is derived from separating or restructuring cellulose into nanoscale fibers or crystals. It can be functionalized to give positively and/or negatively charged groups or coordinating groups to its surface. The processing can consist of oxidation, hydrolysis, mechanical fibrillation or a combination of these processes. Although the use of renewable cellulose is beneficial, the use of chemicals and fibrillation energy needs to be included in the environmental assessment.

The biomass-derived carbon nanomaterials are obtained by thermal or solvothermal conversion. The product can be carbon dots, carbon nanoparticles or a wider range of carbon structures depending on the preparation. Not all biochar is a nanomaterial. Applying a nanoscale classification requires microscopy, particle-size characterization, and surface analysis. The formation of the composite can help to keep the carbon in a larger, easier-to-handled treatment medium¹⁰. Table 4.2 summarizes the material routes and their main assessment requirements. The qualifications are analytical considerations rather than quantified life-cycle findings.

Material route	Treatment function	Key assessment requirement
Plant-mediated iron materials	Sorption, flocculation, and redox treatment	Verify phase and oxidation state; track dissolved iron and transformation products
Plant-mediated zinc oxide	Photocatalytic treatment of organics	Specify illumination and pH; test zinc release and catalyst retention
Cellulose nanofibers and crystals	Membrane separation and surface binding	Measure wet strength, fouling, breakthrough, and regeneration
Plant-derived carbon dots	Photochemical transformation and sensing	Distinguish detection from removal; quantify recovery and residual carbon

⁹ Singh, P., Rani, N., Kumar, S., Kumar, P., Mohan, B., Pallavi, Bhankar, V., Kataria, N., Kumar, R., & Kumar, K. (2023). Assessing the biomass-based carbon dots and their composites for photocatalytic treatment of wastewater. *Journal of Cleaner Production*, 413, 137474. <https://doi.org/10.1016/j.jclepro.2023.137474> (ScienceDirect)

¹⁰ De, A., Singh, N. B., Guin, M., & Barthwal, S. (2023). Water purification by green synthesized nanomaterials. *Current Pharmaceutical Biotechnology*, 24(1), 101–117. <https://doi.org/10.2174/1389201023666220507030548> (EurekaSelect)

Material route	Treatment function	Key assessment requirement
Biomass carbon–oxide composites	Combined adsorption and photocatalysis	Separate component effects and assess composite durability

VI. CONTAMINANT REMOVAL MECHANISMS

Adsorption is the process of a dissolved contaminant being transferred onto a solid surface. Coordination, electrostatic interactions, hydrogen bonding, and pore accessibility may contribute but their significance will vary based on the material and the pollutant. If the surfaces are charged, the interaction could change with a change in pH. Competition for binding sites or aggregation modification by dissolved salts and natural organic matter. The capacity, breakthrough, and regeneration need to be measured, as well as high initial removal, to characterize a reusable sorbent.

The separation of contaminants is done by a combination of pore exclusion and surface interactions between the membrane and the contaminants. Particles can be trapped by a cellulose network and dissolved species are bound by functional groups. With increasing density, retention can increase and permeability can decrease. However, an open network allows for quicker transport but less exclusion. The design target has been set for an appropriate balance of the water and contaminant, and integrity tests have been performed for the specified water and contaminant in wet operating conditions¹¹.

Photocatalysis involves processes in the light that start chemical conversion. With semiconductors, excitation can create electrons and holes that can directly react or create reactive species. Composites can be affected by the light absorption and charge transport of carbon components. Decrease in absorbance of dyes may be due to adsorption, destruction of the chromophore, or other changes. Additional evidence including removal of total organic carbon is required for mineralization and assessment of the residual products is required for safety.

Redox treatment does not break down the element, but rather changes its chemical form in the case of metals. The reduction of chromium, therefore, needs to be assessed in conjunction with the dissolved total chromium and the fate of the solid or dissolved species formed. Capturing the transformed product and managing the spent treatment material are integral parts of purification. Likewise, a nitrogen-species balance should be completed to identify the end products in the disappearance of nitrate.

VII. SUSTAINABILITY AND OPERATIONAL FEASIBILITY

Sustainability is a relative feature of a whole process. Feedstock collection and pretreatment, the use of precursor chemicals, the use of solvents, thermal processing, water use, treatment energy, recovery, and disposal should be taken into account. Reduced demand for dedicated feedstock may be possible due to plant residues but availability and contamination should be verified. The use of a renewable starting material does not prove that it has a smaller environmental footprint if the comparison is not made with a specific alternative¹².

A convenient functional unit is the volume of water (one cubic metre) of a given quality standard. Comparisons need to be made using the same type of influent, service life, and effluent goals. Energy per volume treated, consumable use, contaminant mass removed and amount of waste generated can be reported collectively. Operating costs are not necessarily set by a laboratory synthesis yield or a material cost.

Another limitation is feedstock variability. Precursor composition may vary with season, maturity, extraction conditions, and storage. Botanical identification, well documented preparation, independent batches of synthesis, and consistent product characterization are thus necessary for reproducibility. Any discrepancies between different batches should be reported and cannot be masked in repeated measurements from one batch.

¹¹ Das, R., Lindström, T., Sharma, P. R., Chi, K., & Hsiao, B. S. (2022). Nanocellulose for sustainable water purification. *Chemical Reviews*, 122(9), 8936–9031. <https://doi.org/10.1021/acs.chemrev.1c00683> (ACS Publications)

¹² Lin, N., Dufresne, A., et al. (2021). Nanocellulose-based materials for water treatment: Adsorption, photocatalytic degradation, disinfection, antifouling, and nanofiltration. *International Journal of Molecular Sciences*, 22, 11515. (PubMed Central (PMC))

The recovery of material is particularly significant for suspended nanoparticles. Retention can be easier when immobilized on a support or when incorporated into a membrane, but this may be at the expense of surface area or light exposure. The release of contaminant during regeneration, shedding during use and efficiency of recovery should be measured. The disposal or recovery of spent materials with metals or concentrated pollutants will be decided according to the final composition¹³.

VIII. FRAMEWORK FOR FUTURE EXPERIMENTAL VALIDATION

Experimental study in the future should start with a specific target water and contaminant. Researchers will need to choose a material route that is consistent with the desired mechanism, record synthesis parameters, and determine the properties of independently prepared batches. The relevant techniques are X-ray diffraction (crystalline phases), microscopy (morphology), surface spectroscopy (composition) and electrokinetic measurements (suspension behaviour). The crystallite size derived from the diffraction should not be assumed to be the particle size.

Treatment tests should contain an untreated control, process blank and suitable reference materials. Photocatalytic tests should be performed in conjunction with dark controls, light-only controls, and documentation of the wavelength, irradiance, reactor geometry and temperature. Equilibrium assessment and a contaminant mass balance are needed for adsorption tests. The use of the actual feed should be separated from clean water permeability in the membrane studies¹⁴.

Independent replication should be defined at the synthesis level, the treatment level. Analytical precision is obtained by repeated instrument readings of a sample, but not necessarily batch reproducibility. Sample size, uncertainty, calibration procedures, and detection limits should be reported by the researchers. Model fitting involve examining residuals and uncertainty, a high correlation coefficient is not enough to justify a reaction mechanism.

The improvement of the validation should be carried out from controlled solutions to relevant mixed contaminant waters, and continuous operation. Endpoints include by-products, residual concentration of pollutants, particle release, components of dissolved materials, and performance after re-generation. Chemical testing of contaminants is required for all drinking-water applications, and microbial and final-water quality testing is required for all wastewater applications. No single dye test can prove a water is potable¹⁵.

IX. CONCLUSION

Functional nanostructures derived from plants provide potential solutions in sustainable water treatment via adsorption, membrane separation, photocatalytic degradation and contaminant transformation. Various routes for the creation of functional treatment media include plant extracts, cellulose nanofibers and biomass-derived carbon materials. The literature reviewed shows that they are able to remove some of the metals, dyes and other pollutants under certain experimental conditions. But the choice of material will depend on the contaminant of interest, water type, and desired treatment.

They are utilized in practice if they can be synthesized reproducibly, they are stable in the operated state, they can be efficiently recovered, and they can be effectively regenerated. Laboratory removal efficiencies must be complemented with realistic testing of wastewater, contaminant mass balances and quantification of residual nanoparticles and transformation products. The use of active materials in membranes or hydrogels or re-usable structures will help membranes become more manageable and re-usable, but further testing and evaluation of their performance is needed.

¹³ Khan, M. A., et al. (2021). An updated review on synthetic approaches of green nanomaterials and their application for removal of water pollutants: Current challenges, assessment and future perspectives. *Journal of Environmental Chemical Engineering*, 9(6), 106763. <https://doi.org/10.1016/j.jece.2021.106763> (ScienceDirect)

¹⁴ Singh, N. B., Susan, M. A. B. H., & Guin, M. (2021). Applications of green synthesized nanomaterials in water remediation. *Current Pharmaceutical Biotechnology*, 22(6), 733–761. <https://doi.org/10.2174/1389201021666201027160029> (EurekaSelect)

¹⁵ Ebrahimbabaie, P., Meeinkuirt, W., & Pichtel, J. (2020). Phytoremediation of engineered nanoparticles using aquatic plants: Mechanisms and practical feasibility. *Journal of Environmental Sciences*, 93, 151–163. <https://doi.org/10.1016/j.jes.2020.03.034> (ScienceDirect)

The claim of environmental safety, economic viability, or reduced use of resources cannot be made based on plant origin alone.

Long-term trials of continuous treatment; durability; toxicity assessment; and comparative life-cycle assessment should be emphasized for future research efforts. In addition to purification efficiency, energy needs, chemical use, feedstock supply and waste disposal of spent material should be taken into account. Overall, plant-based nanomaterials are promising to be further developed as part of integrated water-treatment systems. They will need to prove water quality and to show measurable and sustainable environmental benefits against pertinent operating conditions at practical scales to contribute to the purification of the water.

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