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Eco-Friendly Nanocomposites for Sustainable Water Purification: Recent Developments and Future Directions

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ABSTRACT

Increasing water pollution caused by heavy metals, organic compounds, dyes, microplastics, and emerging contaminants has encouraged the development of more efficient and sustainable water purification technologies. This article reviews the advancement of eco-friendly nanocomposites as functional materials for water purification based on scientific literature published between 2019 and 2023. The study employed a Systematic Literature Review (SLR) approach by collecting, evaluating, and synthesizing publications discussing constituent materials, synthesis methods, characterization techniques, purification mechanisms, and implementation challenges of nanocomposites. The findings indicate that combining biopolymers, biochar, and biomass-derived materials with functional nanoparticles significantly enhances specific surface area, adsorption capacity, photocatalytic activity, mechanical stability, and pollutant removal efficiency. Furthermore, green synthesis methods contribute to reducing hazardous chemical consumption while supporting sustainable material production. Nevertheless, large-scale implementation remains challenged by nanoparticle agglomeration, material regeneration, production costs, and potential nanoparticle release into the environment. Future research should prioritize the development of multifunctional nanocomposites that are environmentally safe, cost-effective, easily regenerated, and suitable for sustainable large-scale production to strengthen next-generation water purification technologies.

Keywords: *Adsorption; Biopolymer; Nanocomposite; Water; Water Purification.*

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1.| INTRODUCTION

The availability of clean water is one of the fundamental factors that determine the sustainability of life, public health, and industrial activities. Although the amount of water on earth is very abundant, only a small part of it can be directly utilized as a source of clean water. Population growth, urbanization, industrialization, and increased agricultural activities have led to an increase in the burden of water pollution from heavy metals, organic compounds, synthetic dyes, pharmaceutical residues, pesticides, microplastics, and pathogenic microorganisms. The existence of these various contaminants not only reduces water quality, but also increases risks to human health and ecosystem balance, thus encouraging the need to develop more effective, efficient, and sustainable water purification technology (Bolisetty et al., 2019).

Various water treatment technologies have been developed, such as coagulation-flocculation, sedimentation, sand filtration, ion exchange, advanced oxidation, adsorption, and membrane technology. However, most conventional methods still face various limitations, including low elimination efficiency of micro-sized pollutants, relatively high energy consumption, large amounts of chemical use, the formation of processed sludge, and high operational and maintenance costs. In addition, the development of new types of contaminants such as antibiotics, hormones, perfluoroalkyl compounds (PFAS), and microplastics demands the presence of functional materials with more selective and stable separation capabilities than conventional technologies.

Advances in the field of nanotechnology have opened up new opportunities in the development of water purification materials with superior characteristics. Nanocomposite materials are one of the innovations that are widely developed because they are able to combine two or more materials on the nanoscale so that they produce better physical, chemical, and mechanical properties than the individual constituent materials. High specific surface area, large number of active sites, engineered pore structure, and surface modification capabilities make nanocomposites have higher adsorption capacity, photocatalytic activity, and filtration performance than conventional adsorbents.

In recent years, research attention has begun to shift from the use of synthetic nanomaterials to the development of **e**nvironmentally friendly nanocomposites that prioritize green engineering and sustainability principles. This approach utilizes biopolymers such as cellulose, chitosan, alginate, starch, and lignocellulose biomass as the main matrix combined with metal nanoparticles, metal oxides, graphene oxides, nanoclays, or biochar. The combination not only improves the efficiency of the elimination of various types of pollutants, but also reduces dependence on synthetic materials, reduces environmental impact during the synthesis process, and increases the biodegradability of the resulting materials (Li et al., 2020).

In addition to the constituent materials, the synthesis method is also an important factor in determining the performance of nanocomposites. Various methods such as sol-gel, hydrothermal, in-situ polymerization, electrospinning, and green synthesis continue to be developed to produce a homogeneous, stable, and evenly distributed material structure. Among these various methods, green synthesis is getting more and more attention because it uses plant extracts, microorganisms, and biomass as reducing and stabilizing agents so that it is able to minimize the use of harmful chemicals while reducing energy consumption during the synthesis process. This approach is also in line with the concept of a circular economy and more sustainable material production (Tambovceva et al., 2021).

Eco-friendly nanocomposites have shown very promising potential in removing various contaminants through adsorption mechanisms, photocatalysis, membrane filtration, ion exchange, and antimicrobial activity. Various studies report that the integration of metal oxide nanoparticles, biomass-based carbon, and two-dimensional materials into biopolymer matrices is able to increase active surface area, improve hydrophilic properties, increase resistance to fouling, and extend the life of materials. These characteristics make nanocomposites one of the main candidates in the development of next-generation water treatment technologies that not only have high efficiency but also support environmental sustainability (Kolya & Kang, 2023).

Nonetheless, the development of nanocomposites still faces a number of challenges, such as structural stability during repeated use, the potential release of nanoparticles into the environment, the cost of large-scale production, and the need for standardization of synthesis methods and performance evaluation. In addition, a more comprehensive understanding of the relationship between material composition, synthesis methods, microstructural characteristics, and purification mechanisms is still needed on the effectiveness of the elimination of various types of pollutants. Therefore, this article aims to review the development of environmentally friendly nanocomposites for water purification by focusing on the type of constituent material, synthesis method, working mechanism, factors affecting performance, implementation challenges, and prospects for its development as a sustainable water treatment technology.

2. | RESEARCH METHOD

This study uses the Systematic Literature Review (SLR) method to identify, evaluate, and synthesize various research results regarding the development of environmentally friendly nanocomposites for water purification. The SLR approach was chosen because it is able to present a comprehensive picture of technological developments, material characteristics, synthesis methods, purification mechanisms, and implementation challenges based on published scientific evidence. In addition, this method allows the preparation of an objective analysis through a structured literature selection process so as to reduce the potential for bias in the interpretation of research results.

The literature search process was carried out using Google Scholar as the main database by utilizing a combination of keywords, including eco-friendly nanocomposite, green nanocomposite, water purification, water treatment, adsorption, photocatalysis, biopolymer nanocomposite, biochar nanocomposite, nanomaterials, and environmental remediation. Searches are limited to articles published in the 2019–2023 range to ensure that all references reflect scientific developments relevant to the article's publication in 2024. The prioritized literature is research articles and review articles that have gone through a peer review process and are published in reputable international journals in the fields of engineering, materials, environment, and nanotechnology.

Literature selection is carried out through several stages, namely identification, screening, feasibility assessment, and inclusion. The inclusion criteria include articles that discuss the synthesis, characterization, application, and performance evaluation of environmentally friendly nanocomposites for water purification, either through adsorption mechanisms, photocatalysis, membrane filtration, ion exchange, and other hybrid processes. In contrast, articles that are not directly related to water purification technology, do not have adequate methodological information, or are published outside the 2019–2023 period are not included in the analysis. All literature that meets the criteria is then analyzed qualitatively by grouping information based on the type of constituent material, synthesis method, physical and chemical characteristics, pollutant removal mechanism, factors that affect performance, advantages, limitations, and future development prospects. The results of the synthesis are then used as a basis for compiling a comprehensive discussion on the development of environmentally friendly nanocomposites as a sustainable water purification technology.

3. | RESULTS AND DISCUSSION

The development of nanotechnology has brought significant changes in the field of materials engineering for water treatment. One of the innovations that has received great attention is the development of environmentally friendly nanocomposites that combine biomass-based materials or biopolymers with functional nanoparticles to produce high-performance materials in removing various water contaminants. Compared to conventional materials, nanocomposites offer a larger specific surface area, a greater number of active sites, better mechanical stability, and surface modification capabilities that allow increased selectivity against different types of pollutants (Lestari, 2021).

One of the research trends that developed during the 2019–2023 period is the increasing use of biopolymers as the main matrix in the formation of nanocomposites. Biopolymers such as chitosan, cellulose, alginate, starch, and lignin are chosen because they are biodegradable, biocompatible, easily chemically modifiable, and derived from renewable resources. The presence of hydroxyl, amino, and carboxyl groups in biopolymers provides good adsorption ability to various metal ions and organic compounds. However, pure biopolymers generally have disadvantages of low mechanical stability and resistance to limited operating conditions. Therefore, the integration of biopolymers with metal oxide nanoparticles, activated carbon, biochar, graphene oxide, and nanoclay is a widely applied strategy to increase mechanical strength, increase the active surface area, and increase material adsorption capacity (Hidayanti, 2021).

In addition to biopolymers, biochar is also developing as one of the main materials in the synthesis of environmentally friendly nanocomposites. Biochar is obtained through the process of pyrolysis of biomass under limited oxygen conditions so as to produce a porous carbon material with high stability. The developed pore structure, large surface area, and the presence of oxygen functional groups make biochar effective as an adsorbent for various contaminants. Recent research shows that biochar modification using magnetic nanoparticles such as Fe_3O_4 not only increases adsorption capacity, but also facilitates the process of separating materials after use through the help of magnetic fields. This approach is considered to be able to increase operational efficiency while reducing adsorbent loss during the regeneration process (Rinawati et al., 2019).

The incorporation of metal oxide nanoparticles such as TiO_2, ZnO, Fe_3O_4, and MnO_2 into both biopolymer and biochar matrices provides significant performance improvements. TiO_2 is known to have high photocatalytic activity so it is able to produce hydroxyl radicals when exposed to light with appropriate energy. These radicals play a role in degrading complex organic compounds into simpler molecules and even mineralized into carbon dioxide and water. Meanwhile, ZnO shows good antibacterial activity and has relatively high photocatalytic capabilities. Fe_3O_4 is more widely used due to its magnetic properties so that it supports the efficient separation of adsorbents after use. The integration of several types of nanoparticles in one nanocomposite system produces a synergistic effect that is able to increase the efficiency of eliminating various types of pollutants simultaneously (Dinira, 2022).

The synthesis method is a factor that greatly determines the final characteristics of nanocomposites. Over the past few years, the green synthesis approach has received increasing attention because it is able to reduce the use of harmful solvents and utilize plant extracts, microorganisms, and biomass waste as reducing agents and stabilizing nanoparticles. Compared to conventional synthesis methods, green synthesis produces materials that are more environmentally friendly, reduces energy consumption, and supports the implementation of the concept of green chemistry and the circular economy. In addition, hydrothermal, sol-gel, electrospinning, and in-situ polymerization methods are also still widely used because they are able to produce a more homogeneous distribution of nanoparticles and increase the interaction between the phases of making up nanocomposites (Ginting, 2021).

The development of membrane technology has also led to the use of mixed matrix membrane (MMM) which combines polymers with nano-scale inorganic materials.

This approach aims to address the weaknesses of pure polymer membranes which generally have limitations in terms of thermal stability, mechanical strength, and selectivity. The integration of carbon nanoparticles, zeolites, metal oxides, and metal-organic frameworks (MOFs) is able to improve pore distribution, increase effective surface area, and accelerate the transport of water molecules without reducing the ability to remove contaminants. Therefore, nanocomposite membranes are one of the research focuses in the development of low-pressure water treatment systems that are energy-efficient and have high efficiency against various types of pollutants (Lestari, 2021)

Greater attention is also paid to the elimination of emerging contaminants, which are a group of pollutants whose existence is increasing but cannot be fully addressed by conventional water treatment plants. This group includes antibiotic residues, hormones, personal care products, pesticides, pharmaceutical compounds, perfluoroalkyl and polyfluoroalkyl compounds (PFAS), and microplastics. Complex chemical characteristics make it difficult for many of these contaminants to degrade naturally so that they have the potential to accumulate in the environment. Various studies show that nanocomposites based on biochar, graphene oxide, chitosan, and metal oxide nanoparticles are able to improve the efficiency of the elimination of emerging contaminants through a combination of adsorption, photocatalytic degradation, and advanced oxidation mechanisms. This ability makes nanocomposites one of the potential solutions to face water quality challenges in the future (Basit & Rahmawati, 2023).

The aspect of material regeneration is also an important indicator in determining the feasibility of using nanocomposites on an industrial scale. Adsorbents that have a high capacity but cannot be reused will increase operational costs and produce large amounts of solid waste. Therefore, various studies are trying to develop nanocomposites that have chemical and mechanical stability so that they are able to maintain their adsorption capacity after several cycles of use. Regeneration is generally carried out through washing using acid, alkaline, organic solvents, and thermal solutions. The results show that some biopolymer-based nanocomposites modified with magnetic nanoparticles are still able to retain most of their adsorption capacity after five to ten regeneration cycles, thus providing good prospects for repeated applications (Dinira, 2022).

Nonetheless, the implementation of nanocomposites on a commercial scale still faces various technical challenges. One of the main problems is the tendency of nanoparticles to agglomerate due to high surface energy. Agglomeration causes a reduction in the area of the active surface so as to reduce the effectiveness of adsorption and photocatalytic activity. In addition, the uneven distribution of nanoparticles within a composite matrix can result in inhomogeneous material properties. To overcome these problems, various approaches such as surface functionalization, the use of environmentally friendly surfactants, optimization of synthesis conditions, and interphase bond engineering continue to be developed so that the dispersion stability of nanoparticles can be improved (Nurmalasari & Audina 2020).

In addition to technical aspects, economic factors are also the main consideration in the development of nanocomposite-based water purification technology. Although many studies show excellent laboratory performance, the production costs of some types of nanoparticles are still relatively high, limiting large-scale applications. Therefore, the latest research trends are more towards the use of agricultural waste, forestry waste, fishery waste, and agro-industrial residues as the main raw materials. This approach not only reduces production costs, but also supports the concept of circular economy through the reuse of waste into high-value-added materials. The use of biomass as a source of carbon and biopolymers is also able to reduce dependence on petrochemical-based raw materials so as to produce a more sustainable production process (Rahayu et al., 2019).

The development of Industry 4.0 has also opened up new opportunities in the optimization of nanocomposite designs. The use of machine learning, artificial intelligence, and computational simulation began to be used to predict the relationship between material composition, synthesis conditions, microstructure, and adsorption performance. The data-driven approach allows the material development process to be faster than conventional experimental methods that take a lot of time and money. In addition, molecular dynamics simulations and density functional theory (DFT) are beginning to be used to understand the interaction between nanocomposite surfaces and pollutant molecules at the atomic level, so that they can be used as a basis for designing next-generation materials with higher performance (Zannah, 2020).

Overall, the results of the study show that environmentally friendly nanocomposites have huge prospects as the main material in modern water purification systems. The combination of biopolymers, biochar, and functional nanoparticles is capable of producing materials with high adsorption capacity, good photocatalytic activity, antibacterial properties, and adequate stability for repeated use. On the other hand, challenges such as nanoparticle agglomeration, potential release of nanomaterials, production costs, and limitations of implementation on an industrial scale still require further research. Therefore, the next development direction needs to be focused on the design of multifunctional materials that are safe, economical, easily regenerated, and produced using green synthesis methods so that nanocomposite technology can be widely applied in efficient and sustainable water treatment systems. With this approach, environmentally friendly nanocomposites not only play a role as material innovation, but also as an important part of realizing water treatment technologies that support environmental sustainability, resource efficiency, and resilience to future water quality challenges (Syabriyana et al., 2023).

4. | CONCLUSION

The development of environmentally friendly nanocomposites shows enormous potential as an innovative solution in sustainable water purification technology. The combination of biopolymer, biochar, and biomass-based materials with functional nanoparticles is able to produce materials that have a high surface area, good stability, and the ability to remove various types of contaminants through adsorption mechanisms, photocatalysis, membrane filtration, ion exchange, and antimicrobial activity. Compared to conventional materials, nanocomposites offer higher pollutant removal efficiency while supporting the application of green engineering principles through the use of renewable raw materials and more environmentally friendly synthesis methods.

The results of the study also show that the characteristics of the constituent materials, synthesis methods, distribution of nanoparticles, and physicochemical properties of nanocomposites are the main factors that determine the performance of water purification. In addition, the integration of various treatment mechanisms in a single multifunctional material is a promising approach to improve the effectiveness of the elimination of various types of pollutants, including heavy metals, organic compounds, dyes, microplastics, and new contaminants that are increasingly found in water sources.

However, the application of nanocomposites on an industrial scale still faces a number of challenges, including material stability during repeated use, the potential for release of nanoparticles, regeneration processes, standardization of synthesis methods, and production cost efficiency. Therefore, future research needs to be directed at the development of nanocomposites that are safer, more stable, easy to mass produce, and have a sustainable life cycle. A multidisciplinary approach that integrates materials engineering, nanotechnology, environmental engineering, and circular economy concepts is expected to be able to accelerate the implementation of nanocomposites as water purification technologies that are efficient, environmentally friendly, and able to answer the challenges of clean water needs in the future.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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