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Synthesis and Characterization of Nanocomposites for Water Purification: A Systematic Review

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ABSTRACT

Access to clean water has become a global challenge due to increasing contamination by heavy metals, synthetic dyes, organic compounds, and emerging pollutants that are difficult to remove using conventional water treatment technologies. This study reviews the recent advances in the synthesis, characterization, and performance of nanocomposites for water purification through a Systematic Literature Review (SLR). The reviewed literature was collected from Google Scholar and limited to publications from the last five years, focusing on synthesis methods, characterization techniques, and the effectiveness of nanocomposites in pollutant removal. The findings indicate that synthesis methods, including sol-gel, hydrothermal, co-precipitation, and green synthesis, significantly influence the crystal structure, morphology, surface area, and chemical properties of nanocomposites. Characterization techniques such as XRD, SEM, FTIR, BET, TEM, and UV–Vis provide comprehensive information regarding the relationship between material properties and purification performance. Nanocomposites exhibit excellent capability for removing heavy metals, synthetic dyes, and organic pollutants through adsorption and photocatalytic mechanisms. Furthermore, their regeneration ability highlights their potential as efficient, environmentally friendly, and sustainable materials for advanced water purification technologies.

Keywords: *Adsorption, Characterization, Nanocomposites, Synthesis, Water Purification.*

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1. | INTRODUCTION

The availability of clean water is a major challenge to sustainable development, along with increasing population growth, urbanization, and industrial activities that produce various types of contaminants in aquatic environments. Water pollution is caused not only by heavy metals but also by organic compounds, synthetic dyes, pesticides, antibiotics, and various emerging pollutants that are difficult to remove using conventional water treatment technologies. This situation drives the development of functional materials with high efficiency, good stability, and adequate regeneration capabilities to support more effective and sustainable water purification systems.

Conventional water treatment technologies, such as coagulation-flocculation, sand filtration, sedimentation, and chlorination, have been widely used in water treatment (Hamonangan & Yuniarto, 2022). However, these methods have several limitations, particularly in removing micro- to nano-sized contaminants, persistent organic compounds, and low concentrations of heavy metals. Furthermore, some conventional technologies require high chemical consumption, produce large amounts of sludge, or have low efficiency against complex pollutants. Therefore, the development of advanced materials-based technology has become a focus of research in environmental engineering and materials engineering.

The development of nanotechnology opens up new opportunities to improve the performance of water purification materials through the use of nanoparticles with high specific surface areas, a large number of active sites, and physicochemical characteristics that can be tailored to application needs (Fahmi, M.Z. 2020). Nanoscale materials exhibit significantly higher adsorption capacity, photocatalytic activity, and surface reactivity than conventional materials. However, the use of single nanoparticles still faces several challenges, such as a tendency to agglomerate, difficulty in separation after use, and relatively low stability under certain operational conditions.

To overcome these limitations, research in recent years has focused heavily on the development of nanocomposites. Nanocomposites are materials that combine two or more components at the nanoscale, resulting in synergistic properties not possessed by the individual components. Combinations of metal oxides, carbon materials, polymers, and biomaterials can increase surface area, improve mechanical stability, accelerate electron transfer, and increase the number of active sites involved in adsorption and photocatalysis. These characteristics make nanocomposites one of the most promising materials for modern water purification applications.

Various studies from 2018 to 2022 have shown that nanocomposites based on TiO_2, ZnO, Fe_3O_4, graphene oxide, reduced graphene oxide, biochar, and polymer materials can increase the removal efficiency of heavy metals, dyes, pesticides, antibiotics, and various other organic compounds. In addition to increasing adsorption capacity, modifying the nanocomposite structure can also improve photocatalytic activity by reducing the recombination rate of electron-hole pairs, resulting in more effective pollutant degradation under ultraviolet and visible light irradiation. Several studies have also shown that nanocomposite materials have good regeneration capabilities, potentially reducing operational costs over the long term (Fahmi, M.Z. 2020).

However, most research still focuses on specific types of nanocomposites or evaluates only one water purification mechanism, such as adsorption or photocatalysis, separately. On the other hand, the relationship between synthesis methods, material structural characteristics, and water purification performance has not been comprehensively discussed in a single, integrated study. Furthermore, material characterization using techniques such as X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Brunauer–Emmett–Teller (BET), and UV–Visible Spectroscopy still requires more thorough analysis to explain their relationship to improved material performance.

Based on this description, this article aims to examine the development of nanocomposite synthesis and characterization and their relationship to material performance in water purification applications. The discussion focuses on commonly used synthesis methods, the physicochemical characteristics of the synthesized products, adsorption and photocatalysis mechanisms, and factors influencing the removal efficiency of various contaminants based on scientific publications from 2018–2022. The results of this study are expected to provide.

2. | RESEARCH METHOD

This study employed a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize research findings on the synthesis, characterization, and application of nanocomposites in water purification. The SLR approach was chosen because it yields systematic, transparent, and replicable reviews, making it suitable for providing a comprehensive overview of nanocomposite technology developments based on recent scientific publications. Furthermore, this method allows for the identification of research trends, comparison of material characteristics, and analysis of the relationship between synthesis methods, characterization, and nanocomposite performance in removing various contaminants from water.

The literature search was conducted through the Google Scholar database using a combination of keywords such as nanocomposite, water purification, water treatment, adsorption, photocatalysis, nanomaterials, heavy metal removal, organic pollutant removal, synthesis, and characterization. All literature used was limited to publications from 2018–2022 to align with scientific developments that form the basis for the 2023 technical manuscript. Prioritized publications were research articles and review articles published in reputable international journals that had undergone peer review. The literature selection process was carried out by evaluating the suitability of the title, abstract, keywords, and content of the articles to the research focus, namely nanocomposite synthesis, material characterization techniques, and applications in water purification. Articles that were irrelevant, duplicate, unavailable in full text, or did not meet the publication year range were excluded from the analysis process.

Literature that meets the criteria is then analyzed descriptively and comparatively to obtain information on the types of materials that make up nanocomposites (Hidayanti, 2021). Physics of Materials: Biocomposite Materials.), synthesis methods used, characterization techniques such as X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), Brunauer–Emmett–Teller (BET), Transmission Electron Microscopy (TEM), and UV–Visible Spectroscopy (UV–Vis), as well as performance parameters in water purification applications, including pollutant removal efficiency, adsorption capacity, photocatalytic activity, regeneration ability, and material stability. Furthermore, the results of various studies are compared to identify trends in technological development, the advantages and limitations of each type of nanocomposite, and opportunities for future material development. The synthesis of this information forms the basis for compiling a comprehensive discussion on the relationship between material characteristics and nanocomposite performance in water purification applications.

3. | RESULTS AND DISCUSSION

A literature review shows that research on nanocomposites for water purification applications has increased significantly during the 2018–2022 period . This increase is driven by the need for materials capable of overcoming the limitations of conventional water treatment technologies, particularly in the removal of heavy metals, synthetic dyes, persistent organic compounds, antibiotics, and emerging contaminants. Various studies have reported that nanocomposites offer a combination of physical, chemical, and mechanical properties superior to single materials due to the synergistic effects between their constituent components. High surface area, a greater number of active sites, and improved electron transfer capabilities are key factors contributing to increased water purification efficiency (Lestari, 2021).

Based on the literature analyzed, the most commonly used synthesis methods include sol-gel, hydrothermal, co-precipitation, chemical reduction, and green synthesis (Syifa, 2019). Each method produces different morphological characteristics and crystal structures, which influence material performance. Hydrothermal methods generally produce a more uniform particle size distribution and high crystallinity, while sol-gel methods provide better control over the homogeneity of material composition. On the other hand, green synthesis approaches are gaining widespread development because they can reduce the use of hazardous chemicals and support the concept of environmentally friendly materials without compromising the quality of the resulting nanocomposites (Prayoga, 2022).

Material characterization is a crucial step in ensuring the success of nanocomposite synthesis. Nearly all studies utilize X-ray diffraction (XRD) to identify the crystalline phase and degree of crystallinity of the material (Fricilia, N. 2019). Clear diffraction patterns indicate the successful formation of a crystalline structure and prove that the synthesis process does not result in the formation of significant impurities. Furthermore, characterization using Scanning Electron Microscopy (SEM) and

Transmission Electron Microscopy (TEM) shows that most nanocomposites have a porous morphology with a relatively even distribution of nanoparticles on the surface of the support material. This structure contributes to an increased active surface area, which plays a role in adsorption and photocatalysis.

Analysis using Fourier Transform Infrared Spectroscopy (FTIR) revealed the presence of various functional groups, such as hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O), and metal–oxygen bonds, which act as active sites in the interaction with contaminants. These functional groups enhance adsorption capacity through the formation of electrostatic bonds, complexation, and hydrogen bonds. Meanwhile, Brunauer–Emmett–Teller (BET) testing showed that increasing specific surface area generally correlates positively with increasing material adsorption capacity. The larger the surface area and pore volume, the more pollutant molecules can interact with the nanocomposite surface.

In addition to adsorption, photocatalysis is a key advantage of metal oxide-based nanocomposites. Materials such as TiO_2, ZnO, Fe_3O_4, and graphene-based composites have demonstrated the ability to generate electron–hole pairs when exposed to light energy. These electrons and holes then form oxidative species such as hydroxyl radicals (•OH) and superoxide radicals ($O_2{\bullet}^-$), which are capable of degrading various organic compounds into simpler, less harmful compounds. The incorporation of carbon materials, such as graphene oxide or reduced graphene oxide, has been shown to suppress electron–hole recombination, significantly increasing photocatalytic efficiency compared to the use of single nanoparticles (Fatimah, I. 2020).

Various publications also show that nanocomposites are effective in removing heavy metals such as Pb(II), Cd(II), Cr(VI), Hg(II), and As(V). The heavy metal removal mechanism relies not only on physical adsorption but also involves ion exchange, surface complexation, and electrostatic interactions influenced by solution pH and the type of functional groups on the material surface (Amalia et al., 2022). At optimum pH conditions, the number of charged active sites increases, resulting in stronger interactions between the material and metal ions. Therefore, pH control is one of the most important operational parameters determining the success of the water purification process using nanocomposites. (Izzah, A. 2019). In addition to heavy metals, nanocomposites are also widely applied to remove synthetic dyes such as methylene blue, rhodamine B, methyl orange, and Congo red, which are commonly found in industrial waste.

4. | CONCLUSION

This a research demonstrates that nanocomposites are functional materials with significant potential to support the development of more effective and sustainable water purification technologies. Based on the literature review, the combination of two or more materials at the nanoscale can produce synergistic properties, including increased specific surface area, number of active sites, structural stability, and electron transfer capacity, which contribute to increased removal efficiency for various contaminants.

Synthetic methods, such as sol-gel, hydrothermal, co-precipitation, chemical reduction, and green synthesis, play a crucial role in determining the physicochemical characteristics of nanocomposites, which in turn influence their performance in adsorption and photocatalysis. Characterization results using XRD, SEM, TEM, FTIR, BET, and UV–Vis techniques provide comprehensive information on the crystal structure, morphology, functional groups, surface area, and optical properties of the materials, which are closely related to water purification performance.

Nanocomposites demonstrate excellent ability to remove heavy metals, synthetic dyes, and various organic compounds through adsorption and photocatalysis mechanisms. In addition to having high removal efficiency, several types of nanocomposites also show good regeneration capabilities, thus potentially reducing operational costs in long-term use. However, further development is still needed to improve material stability, simplify the synthesis process, reduce production costs, and ensure environmental safety on a wider application scale. Therefore, optimization of material composition, environmentally friendly synthesis methods, and testing under real-life operational conditions are important research directions to support the implementation of nanocomposites as an efficient, economical, and sustainable water purification technology.

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

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