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Development of Biomass-Based Adsorbents for Sustainable Wastewater Treatment

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ABSTRACT

The increasing generation of wastewater containing various organic and inorganic contaminants has encouraged the development of more efficient and sustainable treatment technologies. Among the available approaches, adsorption using biomass-based materials has gained significant attention due to its low production cost, abundant raw material availability, and environmentally friendly characteristics. This study aims to review recent advances in biomass-based adsorbents for wastewater treatment based on scientific publications from last five years using a Systematic Literature Review (SLR) approach. The review focuses on biomass sources, adsorbent preparation and activation methods, material characterization, adsorption mechanisms, operational factors affecting adsorption performance, and potential applications in wastewater treatment systems. The findings indicate that physical and chemical activation significantly improve surface area, pore volume, and active functional groups, thereby enhancing adsorption capacity toward heavy metals, dyes, and various organic pollutants. In addition to achieving high removal efficiency, biomass-based adsorbents support green technology, circular economy principles, and waste valorization by converting biomass residues into value-added materials. Nevertheless, further studies are required to improve adsorbent regeneration, long-term stability, synthesis standardization, and large-scale industrial implementation to strengthen the development of sustainable wastewater treatment technologies.

Keywords: *Biomass Adsorbent, Circular Economy, Green Technology, Wastewater, Wastewater Treatment.*

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1. | INTRODUCTION

Increased industrial, agricultural, and domestic activities in recent decades have led to a significant increase in the amount of wastewater containing various organic and inorganic contaminants (Yusuf et al., 2023). This waste generally contains heavy metals, synthetic dyes, pharmaceutical compounds, pesticides, phenols, and organic materials with high Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) values. If not adequately treated, the presence of these contaminants can degrade water quality, disrupt ecosystem balance, and pose risks to human health. This situation has driven the development of more efficient, economical, and sustainable wastewater treatment technologies to meet environmental protection demands while supporting sustainable development (Wahida & Uyun, 2023).

Various wastewater treatment methods have been implemented, such as coagulation-flocculation, advanced oxidation, membrane filtration, ion exchange, biological processes, and adsorption. Each method has advantages and limitations, particularly related to investment costs, energy consumption, secondary sludge formation, operational complexity, and effectiveness against various types of pollutants. Among these various technologies, adsorption is one of the most widely developed methods because it has high removal efficiency, a relatively simple operating process, flexibility towards various types of contaminants, and is easy to integrate with other processing units (Darmokoesoemo, 2019). In addition, the adsorption process can be applied on a laboratory or industrial scale with relatively low operational costs. Commercial activated carbon is a widely used adsorbent because it has a high specific surface area and adsorption capacity (Kosim et al., 2022). However, the production cost of activated carbon is still relatively expensive, mainly due to the use of high-quality raw materials and the activation process that requires large amounts of energy. On the other hand, repeated regeneration of activated carbon can also reduce adsorption performance, thereby increasing operational costs.

Therefore, research in recent years has focused on the development of alternative adsorbents that are more economical, easily obtained, and have a lower environmental impact, one of which is through the use of biomass as an adsorbent raw material. Biomass is an organic material derived from agricultural, forestry, and agro-industrial waste, generally composed of cellulose, hemicellulose, and lignin. These components contain various active functional groups, such as hydroxyl, carboxyl, carbonyl, and phenolic, which play a role in the contaminant binding process through physical and chemical adsorption mechanisms (Sepriyani, 2022). In addition to direct use, biomass can also be modified through carbonization, physical activation, or chemical activation to increase surface area, pore volume, and the number of active groups, thereby significantly increasing its adsorption capacity. Various studies have reported that biomass-based adsorbents can remove heavy metals, dyes, antibiotics, pesticides, and various organic pollutants with competitive efficiency compared to conventional adsorbents.

Research developments in the 2019–2023 period also indicate a shift in focus from simply utilizing biomass waste to engineering adsorbent materials with improved surface characteristics, higher adsorption capacity, and enhanced regeneration capabilities. Characterization using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Brunauer–Emmett–Teller (BET), and X-ray Diffraction (XRD) is increasingly being used to understand the relationship between material structure and adsorption mechanisms. Furthermore, analysis of adsorption isotherms, kinetics, and regeneration studies are crucial in evaluating the feasibility of adsorbents for long-term applications (Puspitasari et al., 2023). This approach strengthens the development of biomass-based adsorbents as functional materials that are not only affordable but also have scientifically reliable performance (Rinawati et al., 2019).

Sawit (2023) states that, in addition to technical aspects, the use of biomass as an adsorbent is also in line with the concepts of a circular economy and green technology because it can increase the added value of organic waste through the waste valorization process. The use of biomass as an adsorbent raw material can reduce the volume of solid waste while providing environmentally friendly water treatment materials, thereby contributing to resource efficiency and achieving sustainable development goals (Arifin et al., 2023). However, challenges remain related to standardization of synthesis methods, optimization of activation conditions, adsorbent stability, regeneration, and industrial-scale implementation, which require further study.Based on these conditions, this article aims to examine the development of biomass-based adsorbents in wastewater treatment through a Systematic Literature Review (SLR) approach. The discussion focuses on the characteristics of biomass as an adsorbent, preparation and material modification methods, adsorption mechanisms, factors influencing adsorbent performance, and its potential application as an efficient and sustainable wastewater treatment technology, based on scientific publications from 2019–2023.

2. | RESEARCH METHOD

This study employed the Systematic Literature Review (SLR) method, a literature review aimed at identifying, evaluating, and synthesizing research findings related to the development of biomass-based adsorbents for wastewater treatment in a systematic, transparent, and accountable manner (Zahro, 2023). The SLR approach was chosen because it provides a comprehensive overview of research developments, technological trends, adsorbent material characteristics, and the effectiveness of biomass application in adsorption processes, based on the latest scientific evidence. All literature analyzed was derived from scientific articles published between 2019 and 2023, thus reflecting research developments relevant to the state of science and technology through 2024 (Amukti et al., 2023).The literature search was conducted using Google Scholar as the primary database, using a combination of keywords including biomass adsorbent, biomass-based adsorbent, wastewater treatment, biosorbent, activated carbon from biomass, adsorption, heavy metal removal, organic pollutant removal, biochar, lignocellulosic biomass, and water purification. The obtained articles were then selected based on inclusion and exclusion criteria. Inclusion criteria included original research articles and review articles published in reputable scientific journals between 2019 and 2023, discussing biomass-based adsorbents for wastewater treatment, presenting material characterization and adsorption performance evaluation, and available in full text.

Conversely, articles published before 2019, not undergoing peer review, not relevant to the research topic, or only in the form of conference proceedings, editorials, and abstracts were excluded from the analysis process.The analysis stages were carried out through literature identification, screening based on title and abstract, evaluating the suitability of article content, and synthesizing information from literature that met the criteria (Wibowo & Putri, 2021). The extracted data included the type of biomass used, adsorbent preparation and activation methods, material characterization techniques, operational parameters of the adsorption process, types of pollutants removed, adsorption capacity, contaminant removal efficiency, adsorption isotherm and kinetics models, adsorbent regeneration ability, and potential implementation in wastewater treatment systems. Furthermore, all information was analyzed descriptively and comparatively to identify technological developments, the advantages and limitations of each approach, and opportunities for developing biomass-based adsorbents as environmentally friendly materials that support the concepts of sustainability and a circular economy in wastewater treatment.

3| RESULTS AND DISCUSSION

Literature synthesis results indicate that the development of biomass-based adsorbents experienced a significant increase during the 2019–2023 period in response to the need for more efficient, economical, and sustainable wastewater treatment technologies. Biomass is no longer viewed as a valueless organic waste but has evolved into an alternative raw material for producing high-performance adsorbents through various physical and chemical modification techniques. This development is driven by the abundant availability of biomass, its relatively low production costs, and its lignocellulose content, which allows the formation of active functional groups as adsorption sites for various types of contaminants (Rinawati et al., 2019). Utilization of Rice Husk Activated Carbon as a Phenanthrene Adsorbent in Solid Phase Extraction. Various studies also show that the use of biomass as an adsorbent supports the concepts of green technology, waste valorization, and a circular economy because it can increase the added value of waste while reducing the burden of environmental pollution.Most biomass used as adsorbents comes from agricultural, forestry, and agro-industrial waste, such as coconut shells, rice husks, corn cobs, coffee husks, banana peels, bagasse, sawdust, straw, and various other lignocellulosic residues.

These materials contain cellulose, hemicellulose, and lignin, which are rich in hydroxyl, carboxyl, carbonyl, and phenolic groups. These groups play an important role in the binding process of metal ions and organic compounds through ion exchange, complexation, hydrogen bonding, electrostatic forces, and van der Waals interactions. However, natural biomass generally still has limited surface area and pore volume, so a modification process is needed to increase its adsorption capacity (Yohana, 2023). Adsorbent modification is one of the most widely studied aspects in recent research. Physical activation using water vapor or carbon dioxide can enlarge pore size and increase the surface area of the adsorbent. Meanwhile, chemical activation using potassium hydroxide (KOH), sodium hydroxide (NaOH), phosphoric acid (H_3PO_4), or zinc chloride ($ZnCl_2$) has been shown to produce a more developed pore structure and increase the number of active functional groups on the adsorbent surface.

In addition to activation methods, various studies have also developed adsorbents through controlled carbonization, hydrothermal treatment, metal impregnation, and the formation of biomass-based biochar and activated carbon. These combined processes produce materials with significantly higher adsorption capacities than untreated biomass.Material characterization is a crucial step in elucidating the relationship between adsorbent structure and performance. FTIR spectra are widely used to identify changes in functional groups before and after the adsorption process. SEM analysis shows that the carbonization and activation processes produce a rougher surface with an increased number of pores (Diharyo et al., 2020). BET testing provides information on the specific surface area and pore size distribution that directly affect the adsorption capacity. In addition, XRD analysis is used to determine the level of crystallinity of the material, while EDX is utilized to identify the elemental composition of the adsorbent. The combination of these characterization techniques provides evidence that increasing the surface area and the number of active groups is positively correlated with increasing contaminant removal efficiency.

The effectiveness of biomass-based adsorbents is influenced by various operational parameters, including solution pH, adsorbent dosage, particle size, initial pollutant concentration, temperature, and contact time. The pH value is the most dominant parameter because it determines the surface charge of the adsorbent as well as the form of contaminant speciation in the solution. At appropriate pH conditions, the electrostatic attraction between the adsorbent surface and the pollutant increases, resulting in a higher adsorption capacity. Increasing the adsorbent dosage generally increases removal efficiency because the number of active sites increases, although the adsorption capacity per unit mass may decrease due to surface overlap (particle aggregation). Meanwhile, longer contact times allow adsorption equilibrium to be reached until all active sites are occupied by contaminant molecules or ions.The types of pollutants successfully removed using biomass-based adsorbents are also increasingly diverse.

In addition to heavy metals such as Pb (II), Cd (II), Cr (VI), Cu (II), Ni (II), and Zn (II), recent research shows that biomass adsorbents are effective at removing synthetic dyes, antibiotics, pesticides, phenols, polycyclic aromatic hydrocarbons, and various persistent organic compounds (Rinawati et al., 2019). This ability demonstrates that biomass has the potential to be a multifunctional adsorbent applicable to various industrial and domestic wastewater characteristics. Effectiveness is influenced by the type of biomass, activation method, adsorbent surface characteristics, and the chemical properties of the pollutants being treated. Adsorption isotherm analysis is the primary approach to explaining the interaction between adsorbent and adsorbate. The Langmuir model is the most widely used because it can describe monolayer adsorption on homogeneous surfaces. On the other hand, the Freundlich model is more suitable for heterogeneous adsorbent surfaces with multilayer adsorption processes. Several studies have also utilized the Temkin and Dubinin–Radushkevich models to explain the influence of adsorption energy and pore filling mechanisms. The results of this study indicate that most biomass-based adsorbents follow both the Langmuir and Freundlich models with a high degree of agreement, depending on the material characteristics and the type of pollutant used.

In addition to isotherms, adsorption kinetic models are used to evaluate the rate of contaminant adsorption. The pseudo-second-order model often provides the best fit, indicating that the adsorption process is heavily influenced by chemical interactions (chemisorption) between the adsorbent's functional groups and the contaminant. However, for some unactivated natural biomass, the pseudo-first-order model is still able to describe the physical adsorption mechanism. Several studies have also combined the Elovich and intraparticle diffusion models to explain the internal diffusion process that occurs after surface adsorption. This kinetic analysis provides important information for designing operating times in practical wastewater treatment systems.

Adsorbent regeneration is a key consideration in the development of modern adsorption technology. Regeneration is carried out through a washing process using acidic, alkaline, or specific solvent solutions to release adsorbed contaminants, allowing the material to be reused (Nurhidayah, 2021). The results of various studies indicate that most biomass-based adsorbents maintain their adsorption efficiency after several cycles of use, although there is a slight decrease in capacity due to a reduction in the number of active groups and changes in pore structure. Therefore, optimizing regeneration methods is a major challenge for the economic application of biomass adsorbents on an industrial scale.

Overall, the results of this study indicate that biomass-based adsorbents have excellent prospects as sustainable wastewater treatment materials. The abundant availability of raw materials, relatively low production costs, ease of modification, and the ability to remove a wide range of contaminants make biomass a competitive alternative to commercial activated carbon. However, further research is needed on standardization of the synthesis process, activation optimization, mechanical stability enhancement, long-term regeneration, and implementation in real-scale wastewater treatment systems. These developments are expected to accelerate the use of biomass-based adsorbents as a technology that supports efficient water treatment, waste reduction, and the application of circular economy principles in the environmental sector.

4. | CONCLUSION

The study results indicate that biomass-based adsorbents have enormous potential as alternative materials for wastewater treatment because they combine efficiency, sustainability, and economic value. Various types of lignocellulosic biomass can be utilized as adsorbent raw materials through preparation, carbonization, and activation processes to produce materials with high surface area, pore volume, and active functional groups that can increase adsorption capacity against various contaminants. Characterization using FTIR, SEM, BET, XRD, and EDX plays a crucial role in elucidating the relationship between the physicochemical properties of the adsorbent and the adsorption mechanism. Adsorbent performance is influenced by several operational parameters, such as pH, adsorbent dosage, initial pollutant concentration, contact time, and temperature. Therefore, optimizing process conditions is a key factor in achieving high removal efficiency. Furthermore, the application of adsorption isotherm and kinetics models provides an understanding of the interaction between the adsorbent and adsorbate, which is useful in designing wastewater treatment systems.

The development of biomass-based adsorbents not only provides a solution to water pollution problems but also supports the utilization of organic waste into value-added materials, in line with the concepts of green technology and a circular economy. However, further development is still needed regarding the standardization of the synthesis process, improvement of regeneration capabilities, stability for repeated use, and validation on an industrial scale for biomass-based adsorbents to be more widely applied. Thus, biomass has the potential to become a strategic material in the development of efficient, environmentally friendly, and sustainable wastewater treatment technologies

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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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