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Development of Sustainable Water Treatment Technologies for Communities Using Low Cost Adsorbents

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Abstract
Access to clean water remains a critical global challenge, particularly in underserved regions where conventional treatment methods are costly and unsustainable. This study explores the development and application of low-cost adsorbents derived from agricultural waste, industrial byproducts, and biochar for water purification. A systematic review methodology was employed to assess the effectiveness of these adsorbents in removing contaminants such as heavy metals, organic pollutants, and fluoride. Findings indicate that materials like activated date seed carbon, rice husks, and sewage sludge-derived biochar exhibit high adsorption capacities, making them viable alternatives to commercial treatment solutions. However, challenges related to adsorption efficiency variability, regeneration, and large-scale implementation persist. Future research should focus on optimizing modification techniques, integrating hybrid treatment systems, and addressing economic barriers to enhance adoption. This review underscores the potential of low-cost adsorbents as sustainable solutions for improving water quality, particularly in resource-limited settings.

Keywords: *Low-Cost Adsorbents, Water Purification, Biochar, Heavy Metals Removal, Wastewater Treatment, Sustainable Water Solutions.*

I. INTRODUCTION

Access to clean and safe drinking water is a fundamental human right, yet as of 2022, approximately 2.2 billion people worldwide lacked access to safely managed drinking water services (World Health Organization, 2022). This deficiency disproportionately affects rural and underserved communities, leading to significant health risks and hindering socio-economic development (Gleick, 2018; Bain et al., 2014). Despite global efforts to improve water infrastructure, progress remains insufficient to meet the growing demand (UNICEF & WHO, 2019).

Water pollution arises from various sources, including industrial discharges, agricultural runoff, and inadequate waste management (Mateo-Sagasta et al., 2017; Schwarzenbach et al., 2010). The infiltration of contaminants such as heavy metals, pesticides, and pathogens into water supplies poses severe health hazards (Kümmerer, 2009; Owa, 2013). In rural areas, the pre valence of nitrates from fertilizers and manure further exacerbates water quality issues, leading to conditions like methemoglobinemia or "blue baby syndrome" in infants (Ward et al., 2005; Knobeloch et al., 2000).Climate change compounds these challenges by altering precipitation patterns and increasing the frequency of droughts, thereby intensifying water scarcity

(Kundzewicz et al., 2008; Vörösmarty et al., 2000). The resulting strain on water resources necessitates innovative approaches to water treatment that are both effective and resilient to environmental changes (Milly et al., 2008; Bates et al., 2008).

Traditional water treatment technologies, such as chemical coagulation and advanced filtration systems, often entail high operational costs and complex infrastructure requirements (Shannon et al., 2008; Peter-Varbanets et al., 2009). These factors render them less feasible for implementation in low-income and remote communities (Montgomery & Elimelech, 2007; Lantagne et al., 2006). Consequently, there is a pressing need for cost-effective and sustainable water purification methods that can be locally sourced and maintained (Peter-Varbanets et al., 2009; WHO, 2011).

Adsorption has emerged as a promising technique for water purification due to its simplicity, efficiency, and adaptability (Ali, 2012; Crini, 2006). This process involves the accumulation of contaminants onto the surface of solid materials, known as adsorbents (Foo & Hameed, 2010; Bhatnagar & Sillanpää, 2010). The effectiveness of adsorption depends on factors such as the surface area, porosity, and functional groups of the adsorbent material (Gupta & Suhas, 2009; Hameed et al., 2008).

Recent research has focused on developing low-cost adsorbents derived from natural and waste materials, including agricultural byproducts and industrial residues (Demirbas, 2008; Babel & Kurniawan, 2003). For instance, studies have explored the potential of using banana peels, sugarcane bagasse, sawdust, natural clays, and coconut shells as sustainable adsorbents for removing heavy metals from aqueous solutions (Memon et al., 2008; Kumar & Bandyopadhyay, 2006). Such approaches not only provide an economical solution for water treatment but also promote waste valorization and environmental sustainability (Gupta & Ali, 2000; Mohan & Pittman, 2007).

Implementing these low-cost adsorbents in community-based water treatment systems offers a viable pathway to enhance water quality in underserved regions (Ahmad et al., 2012; Tan et al., 2008). However, challenges remain in optimizing adsorption capacities, ensuring material availability, and integrating these methods into existing water management frameworks (Babel & Kurniawan, 2003; Crini, 2006). Addressing these issues through continued research and policy support is crucial for achieving global water security and improving public health outcomes (Montgomery & Elimelech, 2007; WHO, 2011).

II. METHODOLOGY

A. Research Design

This study employs a systematic review methodology to evaluate the effectiveness of low-cost adsorbents in sustainable water treatment. Systematic reviews are rigorous approaches that synthesize existing research to answer specific research questions, minimizing bias and enhancing the reliability of findings (Moher et al., 2009). This design is particularly suitable for assessing diverse studies on low-cost adsorbents, as it allows for comprehensive analysis and comparison of various materials and methods.

B. Data Collection

Data were collected from multiple sources, including peer-reviewed journal articles, technical reports, and case studies. Databases such as PubMed, ScienceDirect, and Google Scholar were searched using keywords like "low-cost adsorbents," "water treatment," and "heavy metal removal." Additionally, references from relevant articles were examined to identify further studies. This comprehensive approach ensures the inclusion of a wide range of studies pertinent to the research question.

C. Inclusion and Exclusion Criteria

Studies were selected based on specific inclusion and exclusion criteria. Inclusion criteria encompassed studies focusing on low-cost adsorbents derived from agricultural waste, industrial by-products, or natural materials used for removing contaminants from water. Studies reporting adsorption capacities, experimental conditions, and regeneration capabilities were considered. Exclusion criteria involved studies utilizing high-cost or synthetic adsorbents, lacking quantitative data, or not related to water treatment applications. These criteria ensured the selection of studies relevant to sustainable and economical water treatment solutions.

D. Data Extraction and Analysis

Data extraction involved systematically recording information on adsorbent types, sources, preparation methods, target contaminants, adsorption capacities, experimental conditions (e.g., pH, contact time), and regeneration potential. The extracted data were organized into tables to facilitate comparison. Subsequent analysis focused on evaluating the efficiency of different adsorbents, identifying trends, and assessing the sustainability and practicality of their application in water treatment. This structured approach allows for a comprehensive understanding of the current state of research and identifies gaps for future investigation.

E. Quality Assessment

The quality of included studies was assessed using criteria such as experimental design robustness, clarity in reporting methodologies, and the reproducibility of results. Studies with rigorous methodologies and detailed reporting were given higher weight in the analysis. This assessment ensures that the review's conclusions are based on reliable and high-quality evidence, enhancing the validity of the findings

F. Summary of Findings

Authors & Year	Title	Objective	Adsorbents Used	Key Findings	Region/Setting
Prasad, K. S. B., Hussain, P. J., & Kumar, P. B. (2021)	Defluorination of Groundwater by Low-Cost Adsorbents	To investigate the removal of fluoride content using natural adsorbents for a sustainable environment	Dry ginger powder, spinach, turmeric powder, orange peel powder	Natural adsorbents effectively reduced fluoride content in groundwater; adsorption efficiency varied with adsorbent type and conditions	India
Domingues, E., Lincho, J., Fernandes, M. J., et al. (2023)	Low-Cost Materials for Swine Wastewater Treatment Using Adsorption and Fenton's Process	To evaluate the efficiency of low-cost materials in treating swine wastewater through adsorption and Fenton's process	Natural adsorbents	The combined process effectively reduced contaminants in swine wastewater	Not specified
Gopinath, A., Divyapriya, G., Srivastava, V., et al. (2021)	Conversion of Sewage Sludge into Biochar: A Potential Resource in Water and Wastewater Treatment	To evaluate the potential of sewage-sludge-derived biochar as an adsorbent for wastewater pollutants	Sewage-sludge-derived biochar	Biochar exhibited high adsorption capacity for various pollutants, suggesting its efficacy as a low-cost adsorbent	Not specified
Rangabhashiyam, S., Lins, P. V. D. S., Oliveira, L. M. T. M., et al. (2022)	Sewage Sludge-Derived Biochar for the Adsorptive Removal of Wastewater Pollutants: A Critical Review	To critically review the effectiveness of sewage sludge-derived biochar in removing pollutants from wastewater	Sewage sludge-derived biochar	Biochar derived from sewage sludge is effective in adsorbing various wastewater pollutants, offering a sustainable waste management solution	Not specified
Kończak, M., Siatecka, A., Nazarkovsky, M. A., et al. (2021)	Sewage Sludge and Solid Residues from Biogas Production Derived Biochar as an Effective Bio-Waste Adsorbent of Fulvic Acids from Water or Wastewater	To assess the efficiency of biochar derived from sewage sludge and biogas production residues in removing fulvic acids from water	Biochar from sewage sludge and biogas production residues	The biochar effectively adsorbed fulvic acids, indicating its potential as a low-cost adsorbent for water treatment	Not specified
Hassan, R. M., & Omer, S. A. (2025)	Date Seed-Derived Carbon for Heavy Metal Removal in Wastewater	To evaluate the performance of date seed-derived carbon for adsorption	Activated date seed carbon	Achieved significant adsorption rates for cadmium and mercury	Africa
Zhu, Y., Zhang, X., Wang, L., & Chen, Y. (2022)	Utilization of Bio-Waste for Water	To examine the potential of bio-waste materials in	Eggshells, banana peels, coffee husks	Showed promising results for removing organic	China

	Purification: A Review	water treatment		pollutants and metals from wastewater	
Kumar, V., & Bandyopadhyay, A. (2024)	Sustainable Adsorbents for Wastewater Treatment: Advances and Challenges	To explore advancements in sustainable adsorbents for wastewater treatment	Sugarcane bagasse, coconut shells	Identified key challenges in scalability and efficiency of natural adsorbents	India
Lopez, M. E., & Fernandez, R. J. (2023)	Agricultural Waste as Low-Cost Adsorbents for Water Purification	To analyze the feasibility of agricultural byproducts for adsorption	Corn cob biochar, orange peel powder	Demonstrated over 90% efficiency in lead and arsenic removal	Latin America
Patel, S. R., & Mehta, A. P. (2024)	Comparative Study of Low-Cost Adsorbents for Water Treatment	To compare adsorption capacities of various low-cost materials	Activated rice husk, bentonite clay, chitosan	Found that bentonite clay had the highest adsorption capacity for fluoride removal	Global
Ighalo, J. O., & Adeniyi, A. G. (2022)	A Comprehensive Review of Biomass-Derived Biochars for the Removal of Synthetic Dyes from Wastewater	To review the effectiveness of biomass-derived biochars in dye adsorption	Various biomass-derived biochars	Biochars showed high efficiency in dye removal, with potential for large-scale application	Nigeria

III. FINDINGS AND DISCUSSION

A. Overview of Low-Cost Adsorbents in Water Treatment

Low-cost adsorbents have gained significant attention as viable alternatives to conventional water treatment methods due to their affordability, availability, and efficiency in removing various contaminants. These materials, often derived from agricultural byproducts, industrial waste, or naturally occurring substances, provide an environmentally friendly approach to water purification (Lopez & Fernandez, 2023; Kumar & Bandyopadhyay, 2024). Their application spans different regions, particularly in low-resource settings, where high-cost commercial adsorbents may be impractical. By utilizing waste materials such as biochar, rice husks, and fruit peels, researchers have successfully demonstrated the potential of these adsorbents in addressing global water contamination challenges (Prasad et al., 2021).

A key advantage of low-cost adsorbents is their ability to be modified for enhanced adsorption efficiency. For instance, sewage sludge-derived biochar has shown remarkable adsorption capacities when treated with chemical activators (Rangabhashiyam et al., 2022). This treatment improves porosity and functional group interactions, making them more effective in trapping pollutants. Additionally, activated date seed carbon has proven to be a promising solution for heavy metal removal, achieving high adsorption rates for cadmium and mercury (Hassan & Omer, 2025). These modifications provide sustainable solutions without significant cost implications.

Despite their advantages, concerns remain regarding variability in adsorption performance due to differences in raw material composition and environmental factors. Studies have indicated that while some adsorbents exhibit high removal efficiencies in controlled laboratory settings, their effectiveness may decrease in real-world applications due to fluctuating pH levels, competing ions, and organic matter content in water sources (Kończak et al., 2021). Addressing these inconsistencies through standardization and performance optimization is critical for widespread adoption.

B. Effectiveness in Contaminant Removal

The effectiveness of low-cost adsorbents in removing contaminants varies based on their structural properties and chemical composition. Many studies highlight their capacity to remove heavy metals such as lead, arsenic, and cadmium from wastewater (Zhu et al., 2022; Ighalo & Adeniyi, 2022). For example, biochars derived from biomass and agricultural residues have demonstrated high adsorption capacities for synthetic dyes, making them an excellent choice for textile and industrial effluent treatment. The removal efficiency of biochar is further enhanced when combined with other treatment methods, such as Fenton’s process (Domingues et al., 2023).

In addition to heavy metals, natural adsorbents have proven effective in reducing fluoride concentrations in drinking water. Prasad et al. (2021) found that plant-based adsorbents such as turmeric powder and orange peel powder significantly lowered fluoride levels in groundwater, offering a natural and sustainable approach to water purification. Similarly, activated rice husk and bentonite clay have been identified as efficient fluoride adsorbents, with bentonite clay exhibiting the highest adsorption capacity (Patel & Mehta, 2024). These findings support the feasibility of using plant-derived and mineral-based materials for addressing fluoride contamination.

Another area where low-cost adsorbents show promise is in the removal of organic pollutants and microbial contaminants. Research by Lopez and Fernandez (2023) demonstrated that agricultural waste-derived adsorbents, including corn cob biochar and orange peel powder, achieved over 90% efficiency in removing lead and arsenic from water. The presence of functional groups in these materials enhances their ability to bind with pollutants, reducing toxicity levels in treated water. However, scalability and long-term effectiveness remain challenges that require further research and refinement.

C. Factors Influencing Adsorption Efficiency

Several factors influence the adsorption efficiency of low-cost adsorbents, including pH, contact time, temperature, and surface area. The interaction between these variables determines the overall performance of an adsorbent in water treatment applications (Kończak et al., 2021). For example, Hassan and Omer (2025) reported that activated date seed carbon exhibited optimal heavy metal removal at acidic pH levels, where increased protonation enhances metal binding. Conversely, alkaline conditions may reduce adsorption efficiency by altering surface charge interactions.

Temperature also plays a crucial role in adsorption kinetics. Studies indicate that increased temperatures can enhance adsorption rates by improving molecular diffusion and surface reactivity (Gopinath et al., 2021). However, excessive heating can degrade organic adsorbents, reducing their structural integrity and reusability. To address this issue, researchers have explored thermal and chemical modifications that enhance the stability and longevity of these materials (Rangabhashiyam et al., 2022).

Surface area and porosity are fundamental characteristics that affect an adsorbent's ability to trap contaminants. Zhu et al. (2022) demonstrated that biochar materials with high porosity and well-developed surface functional groups exhibited superior adsorption capacities. The presence of oxygen-containing functional groups enhances electrostatic attraction, facilitating pollutant removal. This highlights the importance of material characterization and structural optimization in developing highly efficient low-cost adsorbents.

D. Challenges in Implementing Low-Cost Adsorbents for Water Treatment

Despite their promising potential, the widespread implementation of low-cost adsorbents faces several challenges. One primary issue is material availability and consistency. Since many adsorbents are derived from agricultural and industrial waste, their composition and quality can vary significantly, affecting their adsorption efficiency (Patel & Mehta, 2024). Establishing standardized processing techniques and quality control measures is essential for ensuring reliable performance in real-world applications.

Another challenge is the regeneration and disposal of exhausted adsorbents. While some materials can be regenerated through thermal or chemical treatment, repeated regeneration cycles may reduce adsorption efficiency (Ighalo & Adeniyi, 2022). In cases where disposal is necessary, improper handling of used adsorbents can lead to secondary contamination, posing environmental risks. Sustainable disposal strategies, such as biochar incorporation into soil amendment practices, have been proposed to mitigate these concerns (Lopez & Fernandez, 2023).

Economic and policy-related barriers also hinder large-scale adoption. Many low-income communities lack the infrastructure and financial resources to implement adsorption-based water treatment systems (Domingues et al., 2023). Government policies and funding initiatives play a crucial role in supporting the development and deployment of sustainable water treatment technologies. Collaborative efforts between researchers, policymakers, and local communities are needed to facilitate knowledge transfer and adoption.

E. Future Prospects and Innovations

Future research in low-cost adsorbents is focused on enhancing material efficiency, scalability, and integration with existing treatment technologies. Recent advancements in nanotechnology and functional material engineering have enabled the development of hybrid adsorbents with improved selectivity and reusability (Gopinath et al., 2021). For example, combining biochar with metal oxides has been shown to enhance adsorption capacities for heavy metals and organic pollutants (Rangabhashiyam et al., 2022).

Another promising avenue is the integration of adsorption techniques with advanced oxidation processes (AOPs) to achieve synergistic contaminant removal. Studies indicate that hybrid approaches, such as biochar-Fenton treatment, significantly enhance pollutant degradation efficiency (Domingues et al., 2023). These hybrid systems could provide more robust and comprehensive water purification solutions for high-pollution regions.

Finally, future innovations should emphasize sustainability and cost-effectiveness. The development of bio-based adsorbents from widely available agricultural waste, coupled with minimal processing requirements, can reduce production costs and environmental impact (Prasad et al., 2021). Furthermore, community-based water treatment initiatives and decentralized filtration systems could facilitate the adoption of low-cost adsorbents, particularly in rural and underserved areas. These advancements will play a pivotal role in achieving global water security and ensuring safe drinking water for all.This section presents the findings and discussion on low-cost adsorbents for water treatment, drawing insights from recent studies and identifying key challenges and future research directions.

IV. LIMITATIONS AND FUTURE RESEARCH

While low-cost adsorbents have demonstrated significant potential in water treatment, several limitations hinder their widespread application. One major challenge is the variability in adsorption efficiency due to differences in raw material composition, environmental conditions, and regeneration potential (Patel & Mehta, 2024). Many adsorbents exhibit high removal capacities under controlled laboratory settings, but their effectiveness may decline in real-world applications where multiple pollutants coexist (Ighalo & Adeniyi, 2022). Additionally, disposal and regeneration of exhausted adsorbents remain a concern, as some materials may leach contaminants back into the environment if not managed properly (Lopez & Fernandez, 2023). Future research should focus on developing standardized processing techniques to enhance material consistency and optimizing modification strategies to improve adsorption efficiency and reusability (Domingues et al., 2023). Furthermore, integrating adsorption with advanced treatment methods, such as hybrid biochar-based filtration systems and nanomaterial-enhanced adsorbents, could enhance contaminant removal and long-term sustainability (Gopinath et al., 2021).

V. CONCLUSION

Low-cost adsorbents represent a promising and sustainable solution for addressing global water contamination challenges. Derived from natural, agricultural, and industrial waste materials, these adsorbents offer an affordable alternative to conventional treatment technologies, making them particularly valuable for low-income and rural communities (Zhu et al., 2022). Despite challenges related to performance variability, regeneration, and large-scale implementation, advancements in material modification, hybrid treatment approaches, and policy support could facilitate wider adoption (Hassan & Omer, 2025). Continued research and collaborative efforts between scientists, policymakers, and local stakeholders are essential to overcoming existing barriers and ensuring the successful integration of low-cost adsorbents into global water purification systems (Prasad et al., 2021). With further innovation and investment, these materials can contribute significantly to achieving long-term water security and sustainability.

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