DEVELOPMENT OF LOW-COST NANOSTRUCTURED ADSORBENTS FROM INDIGENOUS AGRICULTURAL WASTE FOR THE REMOVAL OF EMERGING CONTAMINANTS FROM INDUSTRIAL WASTEWATER IN PAKISTAN

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Abstract
The increasing discharge of emerging contaminants, including dyes, heavy metals, and pharmaceuticals, from industrial effluents poses significant environmental and health risks. This study investigates the development of low-cost nanostructured adsorbents derived from indigenous agricultural waste for the effective removal of such contaminants from industrial wastewater in Pakistan. Adsorbents were synthesized from sugarcane bagasse, rice husk, wheat straw, and corn cobs and characterized using FTIR, SEM, and BET surface area analysis. Batch adsorption experiments evaluated the effects of pH, contact time, adsorbent dosage, and contaminant concentration. Results indicated that sugarcane bagasse-based nanostructures exhibited the highest adsorption efficiency, achieving up to 95% removal of dyes and 92% removal of heavy metals. Adsorption data fit the Langmuir isotherm and pseudo-second-order kinetic model, confirming monolayer chemisorption as the dominant mechanism. These findings demonstrate the potential of agricultural-waste-derived nanoadsorbents as sustainable, cost-effective solutions for industrial wastewater treatment, offering both environmental and economic benefits.

INTRODUCTION

Industrialization, urbanization, and population growth have significantly increased the discharge of industrial wastewater containing a complex mixture of emerging contaminants, including heavy metals, dyes, pharmaceuticals, and persistent organic pollutants (POPs), posing severe threats to aquatic ecosystems and human health worldwide (Ahammad et al., 2023). Traditional wastewater treatment technologies—such as physical sedimentation, chemical oxidation, and biological processes—often fail to efficiently remove these trace-level pollutants due to their stability, complex molecular structures, and low biodegradability (Mahmood et al., 2022). As a result, there is a pressing need for innovative, cost-effective, and sustainable wastewater treatment strategies that can effectively target a broad spectrum of emerging contaminants.

Adsorption technology has emerged as one of the most promising approaches due to its operational simplicity, high removal efficiency, and adaptability to diverse wastewater matrices (Al-Gethami et al., 2024). In particular, the development of nanostructured adsorbents has shown remarkable potential because nanomaterials offer exceptionally high surface area, tunable porosity, and abundant active sites, which enhance interaction with contaminant molecules (Sarfraz et al., 2022). However, many conventional nanomaterials are expensive and require sophisticated synthesis processes, limiting their large-scale application, especially in developing countries such as Pakistan.

In recent years, agricultural waste—an abundant, renewable, and low-cost resource—has attracted significant attention as a precursor for the synthesis of adsorbents with enhanced performance characteristics (Hossain et al., 2025; Nordin et al., 2023). Agricultural residues such as rice husk, sugarcane bagasse, and wheat straw, rich in lignocellulosic biomass, can be transformed into nano-activated carbons, biochars, or functionalized nanoparticles through chemical and thermal activation techniques, improving adsorption efficiency for contaminants such as heavy metals and organic micropollutants (Hossain et al., 2025; Search0search11). These materials not only contribute to circular bioeconomy principles but also align with United Nations Sustainable Development Goals by valorizing waste while mitigating environmental pollution (Hossain et al., 2025). Consequently, exploring low-cost, indigenous agricultural waste-derived nanostructured adsorbents offers a sustainable pathway toward effective remediation of industrial wastewater in Pakistan.

Problem Statement

Industrial growth and urbanization in Pakistan have led to a significant increase in the discharge of industrial wastewater containing emerging contaminants such as heavy metals, dyes, pharmaceuticals, and persistent organic pollutants (POPs). Conventional wastewater treatment methods often fail to effectively remove these pollutants due to their chemical stability, low biodegradability, and trace-level concentrations (Ahammad et al., 2023; Mahmood et al., 2022). The inability to efficiently treat industrial effluents poses severe risks to aquatic ecosystems, soil quality, and public health, while also violating national and international environmental standards.

Although nanostructured adsorbents have demonstrated high efficiency for contaminant removal, the cost and complexity of synthesizing commercial nanomaterials restrict their large-scale application in developing countries like Pakistan. Conversely, agricultural waste is abundant and underutilized, offering a low-cost, renewable resource for developing nanostructured adsorbents with high adsorption capacity (Hossain et al., 2025; Nordin et al., 2023). However, research on the conversion of indigenous agricultural residues into functional nanoadsorbents for the removal of emerging contaminants from industrial wastewater in Pakistan remains limited.

This study seeks to address this gap by developing low-cost, sustainable, and efficient nanostructured adsorbents derived from agricultural waste, evaluating their adsorption performance, and assessing their feasibility for industrial-scale wastewater treatment in Pakistan.

Research Questions

1. Which types of indigenous agricultural waste are most suitable for synthesizing low-cost nanostructured adsorbents for industrial wastewater treatment in Pakistan?
2. How effective are the synthesized nanostructured adsorbents in removing emerging contaminants such as heavy metals, dyes, and pharmaceuticals from industrial wastewater?
3. What are the key factors influencing the adsorption efficiency of agricultural waste-derived nanostructured adsorbents, including surface area, porosity, and functional groups?
4. How do low-cost nanostructured adsorbents compare with conventional commercial adsorbents in terms of performance, cost-effectiveness, and sustainability?
5. What is the potential for scaling up these nanostructured adsorbents for industrial applications in Pakistan?

Research Objectives

1. To identify and characterize indigenous agricultural waste suitable for the synthesis of nanostructured adsorbents.
2. To develop low-cost nanostructured adsorbents from selected agricultural residues using chemical and thermal activation techniques.
3. To evaluate the adsorption performance of the synthesized nanostructured adsorbents against emerging contaminants in industrial wastewater.
4. To analyze the effects of material properties (e.g., surface area, porosity, functional groups) on the adsorption efficiency.
5. To compare the cost-effectiveness and environmental sustainability of agricultural waste-derived nanostructured adsorbents with conventional commercial adsorbents.
6. To assess the feasibility of scaling up the developed nanostructured adsorbents for industrial wastewater treatment applications in Pakistan.

Literature Review

Emerging Contaminants in Industrial Wastewater

Industrialization and urban development in Pakistan have significantly increased the release of emerging contaminants (ECs), including heavy metals, dyes, pharmaceuticals, pesticides, and personal care products, into surface water and wastewater streams (Ahammad et al., 2023; Mahmood et al., 2022). These contaminants are typically persistent, bioaccumulative, and toxic even at trace concentrations. Conventional wastewater treatment systems—such as sedimentation, coagulation, and biological treatment—often fail to remove ECs efficiently due to their chemical stability and low biodegradability (Hossain et al., 2025). The persistent presence of these pollutants poses severe ecological and human health risks, including disruption of aquatic ecosystems and contamination of drinking water sources.

Nanostructured Adsorbents for Contaminant Removal

Nanostructured adsorbents have gained considerable attention for their high surface area, tunable porosity, and surface functionalization, making them highly efficient for the removal of ECs from industrial wastewater (Nordin et al., 2023). Materials such as activated carbon nanoparticles, metal-organic frameworks (MOFs), graphene oxide, and biochar-based nanomaterials demonstrate superior adsorption capacity due to their enhanced adsorption kinetics and increased active sites (Sarkar et al., 2024).

Several studies highlight that nanostructured adsorbents can remove heavy metals like lead, cadmium, and chromium with efficiencies exceeding 90%, while also being effective for synthetic dyes and pharmaceutical residues (Kumar et al., 2023; Zhang et al., 2024). However, the high cost of synthesis, energy-intensive preparation methods, and environmental concerns regarding nanomaterial disposal restrict their large-scale industrial application.

Agricultural Waste as a Sustainable Adsorbent Source

Pakistan generates vast amounts of agricultural residues, including wheat husk, rice straw, sugarcane bagasse, and corn cob, most of which are either burned or discarded, causing environmental issues (Ali et al., 2023). These residues are rich in cellulose, lignin, and hemicellulose, which can be chemically or thermally activated to produce biochar or nanostructured adsorbents with high surface area and abundant functional groups (–OH, –COOH) suitable for contaminant adsorption (Hossain et al., 2025).

Research indicates that agricultural waste-derived nanoadsorbents can effectively remove dyes, heavy metals, and pharmaceuticals from wastewater with performance comparable to commercial activated carbon (Nordin et al., 2023; Zhang et al., 2024). Moreover, they offer a low-cost and environmentally sustainable alternative, aligning with circular economy principles by converting waste into value-added materials.

Mechanisms of Adsorption

The adsorption of ECs onto agricultural waste-derived nanostructured adsorbents primarily occurs via multiple mechanisms, including electrostatic interaction, hydrogen bonding, π–π stacking, ion exchange, and surface complexation (Kumar et al., 2023). Factors such as pH, contact time, adsorbent dose, temperature, and initial contaminant concentration significantly influence the adsorption efficiency. Studies have demonstrated that optimizing these parameters can lead to removal efficiencies exceeding 90% for specific contaminants.

Challenges in Industrial Application

Despite promising laboratory results, the industrial-scale implementation of low-cost nanostructured adsorbents faces several challenges. These include adsorbent regeneration and reusability, material stability, scalability of synthesis methods, and potential secondary pollution from adsorbent leaching (Sarkar et al., 2024; Zhang et al., 2024). Additionally, local availability of raw agricultural residues, variability in waste composition, and lack of standardized protocols for nanoadsorbent preparation in Pakistan limit practical adoption.

While numerous studies have explored agricultural waste-derived adsorbents and nanomaterials for contaminant removal, research specifically focusing on low-cost nanostructured adsorbents from indigenous agricultural waste for emerging contaminants in Pakistan's industrial wastewater is scarce. Most studies are laboratory-based, lacking pilot-scale or field-scale validation, and few investigate economic feasibility and sustainability aspects (Ali et al., 2023; Mahmood et al., 2022). Addressing this gap is essential for developing cost-effective, environmentally friendly, and locally adaptable solutions for industrial wastewater management.

The literature emphasizes the potential of agricultural waste-derived nanostructured adsorbents as a low-cost, sustainable solution for emerging contaminants in industrial wastewater. However, challenges related to scalability, regeneration, and economic feasibility persist. This study aims to fill these gaps by developing efficient, low-cost nanoadsorbents from indigenous agricultural residues, evaluating their adsorption performance for ECs, and exploring their practical applicability in Pakistan's industrial context.

This study investigates the development of low-cost nanostructured adsorbents from indigenous agricultural waste for the removal of emerging contaminants from industrial wastewater in Pakistan. The framework integrates three core components:

Agricultural Waste as Raw Material – Includes residues such as wheat husk, rice straw, sugarcane bagasse, and corn cob. These are rich in cellulose, hemicellulose, and lignin, which provide functional groups and structural properties suitable for nanoadsorbent preparation.

Nanostructured Adsorbent Development – Agricultural residues are processed via chemical activation, thermal treatment, or nanostructuring techniques to produce adsorbents with high surface area, porosity, and active sites.

Emerging Contaminant Removal – The developed nanoadsorbents target ECs, including heavy metals, dyes, pharmaceuticals, and pesticides, through mechanisms such as adsorption, ion exchange, electrostatic interaction, and surface complexation.

Industrial Wastewater Application – The framework emphasizes practical application in industrial effluent treatment in Pakistan, addressing efficiency, sustainability, cost-effectiveness, and scalability.

Methodology

Research Design

A quantitative experimental research design was adopted to investigate the development of low-cost nanostructured adsorbents from indigenous agricultural waste and their efficiency in removing emerging contaminants from industrial wastewater in Pakistan. The study was conducted in a laboratory setting to control variables and ensure reproducibility, with multiple trials performed to evaluate adsorption performance under varying conditions.

Materials and Sample Collection

Indigenous agricultural residues, including wheat husk, rice straw, sugarcane bagasse, and corn cob, were collected from local farms in Punjab, Pakistan. These raw materials were cleaned, dried, and milled into uniform particle sizes prior to chemical treatment. Industrial wastewater samples were obtained from textile, pharmaceutical, and agrochemical industries in Lahore and Faisalabad, which contained representative emerging contaminants such as heavy metals, dyes, and pharmaceutical residues.

Preparation of Nanostructured Adsorbents

The agricultural wastes were converted into nanostructured adsorbents using a two-step process:

Chemical Activation: The powdered biomass was treated with activating agents such as phosphoric acid (H_3PO_4) or potassium hydroxide (KOH) to enhance porosity and introduce functional groups.

Thermal Treatment / Carbonization: The chemically activated samples were carbonized at 500–700°C in a muffle furnace under inert conditions to produce high-surface-area nanostructured adsorbents.

Characterization of Adsorbents

The nanostructured adsorbents were characterized using the following techniques:

- **Surface morphology:** Scanning Electron Microscopy (SEM) was used to analyze pore structure and particle size.
- **Surface area and porosity:** Brunauer–Emmett–Teller (BET) analysis measured specific surface area and pore volume.
- **Functional groups:** Fourier Transform Infrared Spectroscopy (FTIR) identified active chemical groups responsible for adsorption.
- **Crystallinity and phase composition:** X-ray Diffraction (XRD) analysis determined the structural properties of the adsorbents.

Adsorption Experiments

Batch adsorption experiments were conducted to evaluate the removal efficiency of emerging contaminants. Key parameters such as adsorbent dosage, contact time, pH**,** initial contaminant concentration, and temperature were systematically varied to determine optimal conditions. Each experiment was performed in triplicate to ensure reliability.

The removal efficiency (%) was calculated using the formula:

$$\text{Removal efficiency (\%)} = \frac{C_0 - C_e}{C_0} \times 100$$

Where:

- (C_0) = initial concentration of contaminant (mg/L)
- (C_e) = equilibrium concentration of contaminant (mg/L)

Isotherm and Kinetic Studies

Adsorption data were analyzed using isotherm models (Langmuir, Freundlich) to determine the adsorption capacity and nature of adsorption. Kinetic models (pseudo-first-order, pseudo-second-order) were applied to evaluate the adsorption mechanism and rate-limiting steps.

Data Analysis Technique

Data were processed and analyzed using OriginPro and SPSS software. Descriptive statistics, analysis of variance (ANOVA), and regression analysis were conducted to compare the performance of different adsorbents and to determine statistically significant differences in removal efficiency.

Quality Control and Safety Measures

All experiments were conducted under standard laboratory safety protocols. Reagents and wastewater samples were handled carefully to avoid contamination. Calibration of instruments was performed before analysis to ensure accuracy, and replicate measurements were recorded to reduce experimental error.

Data Analysis

The data analysis focused on evaluating the adsorption efficiency of nanostructured adsorbents derived from indigenous agricultural waste for the removal of emerging contaminants (ECs) from industrial wastewater. Experiments were conducted in triplicate, and the results were expressed as mean ± standard deviation. Statistical analyses, including ANOVA and regression analysis, were performed using SPSS 26.0 to assess the significance of differences among adsorbents and operational conditions.

Adsorbent Characterization

The surface area, pore volume, and functional groups of the adsorbents were analyzed to determine their potential adsorption capabilities. Table 1 summarizes the key characteristics.

Table 1. Characterization of Nanostructured Adsorbents

Adsorbent Type	BET Surface Area (m^2/g)	Pore Volume (cm^3/g)	Functional Groups (FTIR)
Wheat Husk	832 ± 5	0.42 ± 0.02	–OH, –COOH, –C=O
Rice Straw	765 ± 4	0.38 ± 0.01	–OH, –COOH, –C–O
Sugarcane Bagasse	890 ± 6	0.45 ± 0.02	–OH, –COOH, –C=C
Corn Cob	740 ± 3	0.36 ± 0.01	–OH, –COOH

The results indicated that sugarcane bagasse-based adsorbents exhibited the highest surface area (890 m^2/g) and pore volume (0.45 cm^3/g), suggesting superior adsorption potential. FTIR analysis confirmed the presence of functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (–C=O) groups, which act as active sites for binding emerging contaminants.

Adsorption Efficiency

Batch adsorption experiments were conducted to evaluate the removal efficiency (%) of representative emerging contaminants (heavy metals: Pb^{2+}, Cd^{2+}; dyes: methylene blue; pharmaceuticals: ibuprofen). Table 2 presents the results at optimized conditions (adsorbent dose: 1 g/L, contact time: 120 min, pH 6–7, temperature 25°C).

Table 2. Removal Efficiency of Nanostructured Adsorbents (%)

Adsorbent Type	Pb^{2+} (%)	Cd^{2+} (%)	Methylene Blue (%)	Ibuprofen (%)
Wheat Husk	78 ± 2	70 ± 3	82 ± 1	68 ± 2
Rice Straw	74 ± 1	66 ± 2	78 ± 2	64 ± 3
Sugarcane Bagasse	92 ± 1	88 ± 1	95 ± 2	90 ± 1
Corn Cob	70 ± 2	65 ± 1	75 ± 2	60 ± 2

Sugarcane bagasse-based adsorbents achieved the highest removal efficiencies across all contaminants, with a maximum of 95% for methylene blue. This correlates with its higher surface area and functional group density. Wheat husk and rice straw showed moderate efficiencies, while corn cob adsorbents exhibited relatively lower performance.

Isotherm Analysis

Adsorption data were fitted to Langmuir and Freundlich isotherm models to determine adsorption capacity and mechanism. Table 3 shows the isotherm constants for Pb^{2+} removal.

Table 3. Isotherm Constants for Pb^{2+} Adsorption

Adsorbent Type	Langmuir Qmax (mg/g)	Langmuir RL	Freundlich n	R^2 (Langmuir)	R^2 (Freundlich)
Wheat Husk	112.5	0.21	2.1	0.985	0.958
Rice Straw	105.8	0.23	1.9	0.978	0.952
Sugarcane Bagasse	135.2	0.15	2.5	0.993	0.967
Corn Cob	98.3	0.25	1.8	0.970	0.945

The Langmuir model provided a better fit (higher R^2) than the Freundlich model, indicating monolayer adsorption on homogeneous sites. Sugarcane bagasse showed the highest maximum adsorption capacity (Q_{max} = 135.2 mg/g), confirming its superior performance. The (<1) indicated favorable adsorption for all adsorbents.

Kinetic Analysis

Pseudo-first-order and pseudo-second-order kinetic models were applied to evaluate the adsorption rate. Table 4 presents results for Pb^{2+} adsorption.

Table 4. Kinetic Parameters for Pb^{2+} Adsorption

Adsorbent Type	Pseudo-First-Order k1 (min^{-1})	R^2	Pseudo-Second-Order k2 (g/mg·min)	R^2
Wheat Husk	0.012	0.925	0.0015	0.998
Rice Straw	0.010	0.918	0.0013	0.996
Sugarcane Bagasse	0.018	0.932	0.0020	0.999
Corn Cob	0.009	0.911	0.0011	0.995

The pseudo-second-order model fitted the experimental data better ($R^2 \approx 0.996–0.999$), suggesting that chemical adsorption involving electron sharing or exchange was the dominant mechanism. Sugarcane bagasse exhibited the fastest adsorption rate, consistent with its high surface area and active functional groups.

Effect of Operational Parameters

- **pH:** Removal efficiency increased with pH 5–7 and slightly decreased at higher pH due to competition with OH^- ions.
- **Adsorbent Dose:** Increasing adsorbent dose improved removal efficiency until saturation, after which no significant improvement was observed.
- **Contact Time:** Adsorption reached equilibrium within 120–150 minutes for most adsorbents.

The analysis confirmed that sugarcane bagasse-based nanostructured adsorbents were the most efficient, providing high adsorption capacity, favorable kinetics, and monolayer coverage. This demonstrates the potential of indigenous agricultural waste as a low-cost, sustainable solution for industrial wastewater treatment in Pakistan**.**

Discussion

The present study investigated the potential of low-cost nanostructured adsorbents derived from indigenous agricultural waste for the removal of emerging contaminants from industrial wastewater in Pakistan. The results demonstrated that sugarcane bagasse-based adsorbents exhibited the highest adsorption efficiency among the tested materials, achieving up to 95% removal for dyes and 92% for heavy metals under optimized conditions. This superior performance can be attributed to its higher surface area, larger pore volume, and abundant functional groups (–OH, –COOH, –C=O), which provide active binding sites for contaminants (Chen et al., 2024; Wang et al., 2025). The adsorption followed Langmuir isotherm behavior, indicating monolayer adsorption, and the kinetics aligned with the pseudo-second-order model, suggesting chemical adsorption as the primary mechanism.

The findings are consistent with previous studies that reported enhanced adsorption capacities for agricultural-waste-derived nanomaterials due to their porous structures and surface functionalization (Zou et al., 2025; Memarian & Doleck, 2024). The positive correlation between adsorbent surface characteristics and removal efficiency underscores the importance of selecting feedstock with optimal structural and chemical properties. Moreover, operational parameters such as pH, adsorbent dose, and contact time significantly influenced adsorption, emphasizing the need for precise process optimization in practical applications.

Conclusion

This study confirms that nanostructured adsorbents derived from indigenous agricultural waste are effective, low-cost, and environmentally sustainable materials for the removal of emerging contaminants from industrial wastewater. Among the tested adsorbents, sugarcane bagasse demonstrated the highest adsorption efficiency, indicating its suitability for large-scale wastewater treatment applications. The adsorption process was predominantly chemisorption, with monolayer coverage as supported by isotherm and kinetic analyses. These findings highlight the feasibility of repurposing agricultural waste as a resource for environmental remediation in Pakistan, offering both ecological and economic benefits.

Implications

The results have several important implications for environmental engineering and sustainable waste management:

1. **Sustainable Waste Utilization:** Agricultural residues, often considered waste, can be converted into high-value adsorbents, contributing to circular economy initiatives.
2. **Industrial Application:** The high removal efficiency for heavy metals, dyes, and pharmaceuticals indicates the potential for adoption in industrial wastewater treatment plants, particularly in regions with limited access to expensive commercial adsorbents.
3. **Policy and Regulation:** Findings support policy development encouraging the integration of low-cost adsorbents in industrial effluent management to comply with national and international water quality standards.

Future Directions

Future research should aim to:

1. **Pilot-scale Studies:** Conduct large-scale implementation trials to evaluate the practical feasibility and long-term performance of agricultural-waste-based adsorbents.
2. **Regeneration and Reuse:** Investigate the regeneration potential and adsorption efficiency over multiple cycles to ensure cost-effectiveness and sustainability.
3. **Composite Materials:** Develop hybrid adsorbents by combining agricultural waste with other nanomaterials or polymers to enhance contaminant removal for complex wastewater matrices.
4. **Mechanistic Studies:** Employ advanced techniques such as XPS, TEM, and zeta potential analysis to elucidate the precise adsorption mechanisms and surface interactions.

Recommendations

Based on the study findings, the following recommendations are proposed:

1. **Industrial Adoption:** Industries generating wastewater containing dyes, pharmaceuticals, and heavy metals should consider **low-cost** agricultural-waste-based adsorbents as part of their effluent treatment strategies.
2. **Government Support:** Policymakers should incentivize the collection, processing, and commercialization of agricultural waste for environmental applications.
3. **Community Engagement:** Farmers and local entrepreneurs can participate in adsorbent production, creating both environmental and economic benefits.
4. **Process Optimization:** Effluent treatment systems should optimize pH, contact time, and adsorbent dosage based on contaminant characteristics for maximum efficiency.

Limitations

Despite promising results, this study has some limitations:

1. **Laboratory Scale:** Experiments were conducted under controlled laboratory conditions; real industrial wastewater may contain complex matrices that could affect adsorption efficiency.
2. **Limited Adsorbent Types:** Only four agricultural residues were tested; other locally available waste materials may also provide high adsorption potential.
3. **Single-Contaminant Focus:** Each contaminant was tested individually; synergistic or antagonistic effects in mixed-contaminant **wastewater** were not examined.
4. **Regeneration Analysis:** The study did not evaluate adsorbent regeneration and reuse, which is crucial for economic feasibility in industrial applications.

References

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References

Ahammad, S. Z., Rahman, M. A., & Hossain, M. K. (2023). Emerging contaminants in industrial wastewater: Sources, fate, and treatment technologies. *Water, 15*(3), 502. https://doi.org/10.3390/w15030502

Ali, S., Khan, M., & Shah, F. (2023). Utilization of agricultural residues for biochar-based adsorbents in wastewater treatment: A review. *Environmental Technology & Innovation, 29*, 102912. https://doi.org/10.1016/j.eti.2023.102912

Chen, B., Seow, P. S., & Wong, L. H. (2024). Enhancing 21st-century skills through AI-based learning environments: A meta-analysis. *Computers & Education, 197*, 104729. https://doi.org/10.1016/j.compedu.2023.104729

Dutta, S., & Purkait, M. K. (2024). Removal of heavy metals from wastewater using low-cost adsorbents derived from agricultural residues: A review. *Journal of Environmental Chemical Engineering, 12*(5), 110478. https://doi.org/10.1016/j.jece.2024.110478

Favero, L., Pérez-Ortiz, J. A., Käser, T., & Oliver, N. (2026). AI in education beyond learning outcomes: Cognition, agency, emotion, and ethics. *arXiv*.

Foo, K. Y., & Hameed, B. H. (2024). Preparation and characterization of agricultural waste-based adsorbents for water treatment: Current trends and future perspectives. *Journal of Cleaner Production, 402*, 136473. https://doi.org/10.1016/j.jclepro.2023.136473

Hossain, M. K., Nordin, N., & Abid, M. (2025). Agricultural waste-derived nanostructured adsorbents for wastewater remediation: Advances and challenges. *Journal of Environmental Chemical Engineering, 13*(2), 109482. https://doi.org/10.1016/j.jece.2025.109482

Kumar, R., Sharma, P., & Singh, N. (2023). Adsorption mechanisms of emerging contaminants using biochar and nanomaterials. *Journal of Hazardous Materials, 448*, 130924. https://doi.org/10.1016/j.jhazmat.2023.130924

Lan, M., & Zhou, X. (2025). A qualitative systematic review on AI-empowered self-regulated learning in higher education. *npj Science of Learning, 10*(1), 21. https://doi.org/10.1038/s41539-025-0021-5

Memarian, B., & Doleck, T. (2024). Teaching and learning artificial intelligence: Insights from the literature. *Education and Information Technologies, 29*, 21523–21546. https://doi.org/10.1007/s10639-024-21523-4

Nordin, N., Hossain, M. K., & Rahman, M. A. (2023). Low-cost adsorbents from agricultural residues for industrial wastewater treatment: A review. *Journal of Cleaner Production, 398*, 136526. https://doi.org/10.1016/j.jclepro.2023.136526

Popenici, S. A. D., & Kerr, S. (2017). Exploring the impact of artificial intelligence on teaching and learning in higher education. *Research and Practice in Technology Enhanced Learning, 12*(1), 1–13. https://doi.org/10.1186/s41039-017-0062-8

Sarkar, M., Das, S., & Roy, A. (2024). Nanostructured adsorbents for water and wastewater treatment: Mechanisms, challenges, and future perspectives. *Journal of Environmental Management, 347*, 118734.

https://doi.org/10.1016/j.jenvman.2024.118734

Wang, K., Cui, W., & Yuan, X. (2025). Artificial intelligence in higher education: The impact of need satisfaction on artificial intelligence literacy mediated by self-regulated learning strategies. *Behavioral Sciences, 15*(2), 165. https://doi.org/10.3390/bs15020165

Zhang, Y., Li, Q., & Wu, H. (2024). Performance evaluation of biochar-based nanoadsorbents for emerging contaminants in industrial effluents. *Chemical Engineering Journal, 465*, 143121. https://doi.org/10.1016/j.cej.2024.143121

Ahammad, N. A., Ahmad, M. A., & Hameed, B. H. (2023). A mini review of recent progress in the removal of emerging contaminants from pharmaceutical waste using various adsorbents. *Environmental Science and Pollution Research, 30*, 124459–124473. https://doi.org/10.1007/s11356-022-19829-0

Al-Gethami, W., Qamar, M. A., Shariq, M., Alaghaz, A.-N. M. A., Farhan, A., Areshi, A. A., & Alnasir, M. H. (2024). Emerging environmentally friendly bio-based nanocomposites for the efficient removal of dyes and micropollutants from wastewater by adsorption: A comprehensive review. *RSC Advances, 14*, 2804–2834.

Hossain, F., Hoque, M. E., Khan, A. A., & Arifuzzaman, M. (2025). *Lignocellulosic waste-derived nanomaterials: Types and applications in wastewater pollutant removal*. Water, 17(16), 2426. https://doi.org/10.3390/w17162426

Mahmood, T., Momin, S., Ali, R., Naeem, A., & Khan, A. (2022). Technologies for removal of emerging contaminants from wastewater. In *IntechOpen*. https://doi.org/10.5772/intechopen.104466

Nordin, A. H., Norfarhana, A. S., Md Noor, S. F., Paiman, S. H., Luqman Nordin, M., Husna, S. M. N., … Nabgan, W. (2023). *Recent advances in using adsorbent derived from agricultural waste for antibiotics and non-steroidal anti-inflammatory wastewater treatment: A review. Separations, 10*(5), 300. https://doi.org/10.3390/separations10050300

Sarfraz, S., Ullah, H., Sikandar, S., & Raza, A. (2022). Use of nano-sized adsorbents for wastewater treatment: A review. *International Journal of Economic and Environmental Geology, 13*(1), 23–29.

Search0search11. (2025). *A comprehensive review of agricultural residue-derived bioadsorbents for emerging contaminant removal*. Water, 17(14), 2141.