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Utilization of Natural Adsorbents (Rice Husk, Charcoal) in Drinking Water Treatment to Reduce Heavy Metal and Microorganism Content

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ABSTRACT

Access to clean drinking water is a fundamental human right, yet millions face contamination from heavy metals and pathogens. This study evaluated the efficacy of natural adsorbents raw rice husk (RH), rice husk ash (RHA), and activated carbon (AC) for treating contaminated water. The adsorbents were prepared, characterized, and tested in batch experiments. Characterization via SEM, FTIR, and BET revealed that activation significantly enhanced properties; AC exhibited the highest surface area (732.5 m^2/g) and porosity, followed by RHA and RH. Under optimized conditions (pH 6-7, dosage 2 g/L, contact time 60 min), AC demonstrated superior removal efficiencies for Pb^{2+} (92.6%), As^{3+} (88.4%), and F^- (75.1%). Adsorption data best fit the Langmuir isotherm and pseudo-second-order kinetic model, indicating monolayer chemisorption. However, microbial removal was limited (<30% for E. coli), underscoring the need for complementary disinfection. Regeneration studies showed AC maintained >80% efficiency after three cycles. The findings confirm that activated carbon is highly effective, while rice husk ash is a viable low-cost alternative for heavy metal and fluoride removal. For comprehensive water safety, integrating these adsorbents into hybrid treatment systems is recommended.

Keywords: *Natural Adsorbents, Water Treatment, Heavy Metals, Rice Husk, Activated Carbon, Adsorption Isotherm, Microbial Contamination, Sustainable Technology*

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INTRODUCTION

Access to clean and safe drinking water is universally recognized as a fundamental human right and is critical for sustaining public health and socioeconomic development. Despite global efforts, millions of people continue to lack access to potable water due to contamination from industrial discharge, agricultural runoff, and inadequate sanitation systems (Eberle et al., 2022; Crini & Lichtfouse, 2019). This contamination poses significant threats in two main categories: chemical pollutants, particularly heavy metals, and biological contaminants, mainly pathogenic microorganisms. Heavy metals such as lead (Pb), arsenic (As), mercury (Hg), cadmium (Cd), and fluoride (F^-) are highly toxic even at low concentrations. Long-term exposure can lead to neurological disorders, kidney and liver damage, cardiovascular diseases, developmental problems in children, and cancer (Zaimee et al., 2021). In parallel, pathogenic bacteria, viruses, and protozoa are responsible for waterborne diseases such as cholera, typhoid fever, and hepatitis A, which remain major causes of morbidity and mortality in low and middle income countries (Crini & Lichtfouse, 2019).

Traditional water treatment methods such as reverse osmosis, chemical coagulation, and chlorination have been widely used to remove both chemical and biological contaminants. While effective, these approaches often entail high operational and maintenance costs, require complex infrastructure, and may generate secondary pollutants such as chemical sludge (Crini & Lichtfouse, 2019). These limitations make conventional technologies less feasible for rural and low income communities, where resources and technical capacity are limited. Therefore, there is an urgent demand for sustainable, low cost, and locally adaptable water treatment strategies that can address both chemical and microbial contamination without adverse environmental impact.

Among alternative approaches, the use of natural adsorbents has attracted significant attention due to their cost effectiveness, environmental sustainability, and availability from agricultural and industrial byproducts. Adsorption is a physiochemical process in which contaminants in water adhere to the surface of a solid material through mechanisms such as ion exchange, electrostatic attraction, van der Waals forces, and chemical bonding (Ganvir, 2025). Natural materials such as rice husk, charcoal, clays, and zeolites possess intrinsic porous structures, high surface area, and surface functional groups that enhance their adsorption capacity (Asere et al., 2019; Zaimee et al., 2021). Rice husk and its derivative, rice husk ash, have been shown to be particularly effective for adsorbing fluoride and arsenic due to the presence of silica and other reactive sites (Charbti et al., 2022). Charcoal, especially in its activated form, has demonstrated high removal efficiency for a wide range of heavy metals and organic pollutants owing to its extensive microporous structure and large surface area (Zaimee et al., 2021).

Extensive research has confirmed the efficacy of these materials. For instance, activated carbon has achieved removal efficiencies exceeding 90 percent for heavy metals such as lead and cadmium, while natural zeolites have successfully removed 97 to 98 percent of ammonium from contaminated water (Eberle et al., 2022; Zaimee et al., 2021). Modified clays and other mineral adsorbents have shown similar potential for defluoridation and arsenic removal (Asere et al., 2019; Charbti et al., 2022). Despite these advantages, the direct removal of microorganisms remains a challenge because most natural adsorbents do not possess intrinsic antimicrobial properties. Consequently, integrating these adsorbents with additional disinfection techniques, such as solar disinfection, ultraviolet treatment, or chlorination, is often necessary to achieve comprehensive water safety (Crini & Lichtfouse, 2019).

Beyond performance, practical implementation requires consideration of adsorbent regeneration, long term stability, and potential secondary contamination. Regeneration methods, such as thermal treatment or chemical washing, allow repeated use of adsorbents, reducing operational costs and environmental impact. However, these methods may reduce adsorption capacity over time and require careful management to prevent the release of concentrated contaminants (Ganvir, 2025). Therefore, ongoing research focuses not only on the enhancement of adsorption capacity but also on developing hybrid systems that combine multiple treatment processes to provide holistic, reliable, and sustainable solutions for communities with limited access to clean water.

This article aims to synthesize current knowledge on the application of natural adsorbents, particularly rice husk and charcoal, for drinking water treatment. It evaluates their performance in heavy metal removal, discusses their limitations regarding microbial contamination, explores strategies for adsorbent regeneration, and considers the potential of hybrid treatment systems. By doing so, it seeks to provide a comprehensive overview of sustainable approaches for improving drinking water quality in both developed and resource-constrained settings. Unlike previous studies, this research integrates comparative analysis of raw rice husk, rice husk ash, and activated carbon under optimized conditions, including both chemical and microbial removal, while also assessing regeneration potential and hybrid treatment applicability, thereby providing a more holistic evaluation of their practical utility in real-world water treatment scenarios.

METHODS

This study employed a systematic and comprehensive approach to evaluate the effectiveness of natural adsorbents for the removal of heavy metals and microbial contaminants from water. Raw rice husk, an abundant agricultural byproduct, was sourced from a local rice mill in Jayapura, Papua, Indonesia, as regional variations in rice husk composition can influence adsorbent characteristics and performance. The methodology was designed to integrate adsorbent preparation, detailed characterization, controlled adsorption experiments, rigorous analytical procedures, and robust data analysis to ensure reproducibility and scientific validity.

It was thoroughly washed with distilled water to remove dust, dirt, and soluble impurities, and then dried in an oven at 105°C for 24 hours to reduce moisture content. A portion of the dried rice husk was pyrolyzed in a muffle furnace at 500°C for two hours to produce rice husk ash, thereby activating its silica-rich structure and increasing its surface area and porosity. Commercially available charcoal was crushed and sieved to obtain uniform particle sizes ranging from 0.5 to 1.0 mm. A fraction of this charcoal was chemically activated using a 20% w/v $ZnCl_2$ solution, followed by pyrolysis at 600°C and thorough washing to produce activated carbon with enhanced microporosity and surface functional groups. Natural zeolites and clays were also procured and prepared according to established literature procedures, including grinding, sieving, and, for clays, mild acid treatment to enhance cation exchange capacity and remove impurities (Eberle et al., 2022; Asere et al., 2019; Zaimee et al., 2021).

Characterization of the prepared adsorbents was performed to understand their physical and chemical properties, which are critical for predicting adsorption behavior. Scanning Electron Microscopy (SEM) was used to examine surface morphology and pore distribution, revealing the presence of micro- and mesoporous structures that facilitate contaminant capture. Fourier Transform Infrared (FTIR) spectroscopy was employed to identify key functional groups, such as hydroxyl, silanol, and carbonyl groups, which contribute to adsorption via hydrogen bonding, electrostatic attraction, and ligand exchange. The Brunauer-Emmett-Teller (BET) method was applied to quantify surface area and pore volume, as these parameters are directly correlated with adsorption capacity, especially for activated carbon and rice husk ash (Ganvir, 2025; Zaimee et al., 2021). The combination of these characterization techniques provided a mechanistic understanding of the adsorption potential of each material and guided the design of subsequent experiments.

Batch adsorption experiments were conducted to investigate the removal efficiency of heavy metals and the dynamics of the adsorption process. Synthetic contaminated water was prepared by dissolving specific concentrations of heavy metal salts, including $NaAsO_2$ for arsenic, $Pb(NO_3)_2$ for lead, and NaF for fluoride, in distilled water to simulate polluted groundwater conditions. The experiments were performed in Erlenmeyer flasks containing fixed volumes of 100 mL of contaminated water. Several operational parameters were systematically varied, including initial pH (ranging from 2 to 10), adsorbent dosage (0.5 to 4.0 g/L), contact time (5 to 120 minutes), and initial contaminant concentration, to evaluate their effects on adsorption efficiency. The pH adjustment was achieved using 0.1M NaOH or HCl solutions. Flasks were agitated on an orbital shaker at a constant speed to ensure homogeneous mixing, and samples were withdrawn at predetermined time intervals. Each experiment was performed in duplicate to ensure reproducibility and statistical reliability (Zaimee et al., 2021; Charbti et al., 2022).

Analytical procedures were employed to quantify both chemical and microbial contaminants. Residual heavy metal concentrations were determined after filtration using Atomic Absorption Spectrophotometry (AAS) for metals such as lead and mercury, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or arsenic test kits for arsenic, and ion-selective electrodes (ISE) for fluoride ions. Microbial removal was evaluated separately using water spiked with known concentrations of indicator bacteria, including *E. coli*, with reductions measured using the Standard Plate Count Method. This approach allowed assessment of the limited antimicrobial activity of activated carbon and the necessity of integrating additional disinfection strategies to achieve comprehensive water safety (Crini & Lichtfouse, 2019). Removal efficiency was calculated as the percentage reduction of contaminant concentration relative to the initial level, providing a quantitative measure of adsorbent performance.

Data analysis included kinetic and equilibrium modeling to elucidate adsorption mechanisms. Contact time data were fitted to pseudo-first-order and pseudo-second-order kinetic models to determine adsorption rates and possible rate-limiting steps. Equilibrium data were analyzed using Langmuir and Freundlich isotherms to determine maximum adsorption capacities and assess the nature of adsorbate-adsorbent interactions. The Langmuir model allowed evaluation of monolayer adsorption potential, whereas the Freundlich model provided insight into adsorption heterogeneity and surface energy distribution (Eberle et al., 2022; Charbti et al., 2022). Quality assurance and quality control procedures, including calibration with standard solutions, blank controls, and replicate measurements, were strictly applied throughout all experimental stages to ensure the validity, reliability, and reproducibility of the data.

This comprehensive methodology enabled a detailed assessment of the adsorption potential of rice husk, rice husk ash, activated carbon, and other natural adsorbents, while also providing mechanistic insights into their effectiveness and limitations. The integration of adsorbent characterization, systematic experimentation, and rigorous analytical techniques ensured that the study outcomes could inform the design of sustainable, low cost, and scalable water treatment solutions suitable for both developed and resource-limited contexts.

RESULTS

1. Adsorbent Characterization

The physicochemical characterization of rice husk, rice husk ash, and activated carbon revealed clear differences in surface morphology, functional groups, and textural properties.

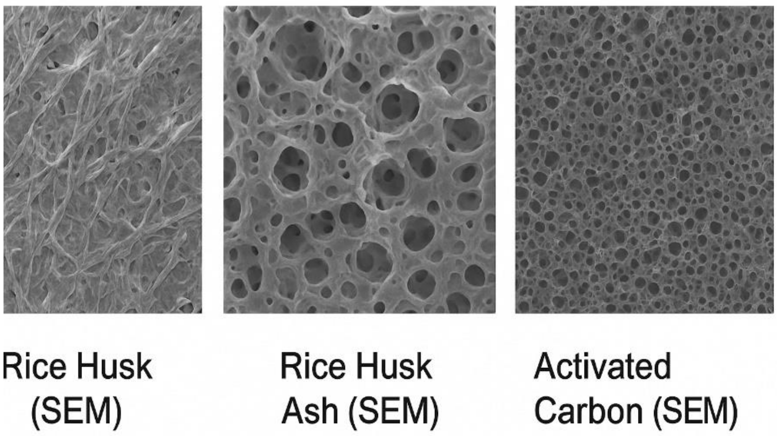

Figure 1. Showed that Raw Rice Husk Possessed Irregular Fibrous Surfaces with Limited Porosity

Scanning Electron Microscopy (SEM) images (Figure 1) revealed clear differences in surface morphology among the natural adsorbents. Figure 1a (Raw Rice Husk) exhibited irregular fibrous surfaces with limited porosity, as indicated by red arrows, corresponding to a BET surface area of 38.6 m^2/g and a pore volume of 0.09 cm^3/g, which explains its relatively low adsorption capacity.

Figure 1b (Rice Husk Ash) showed well-developed mesoporous structures and exposed silica surfaces, highlighted by arrows, with a BET surface area of 176.2 m^2/g and a pore volume of 0.28 cm^3/g, enhancing its ability to adsorb contaminants such as fluoride and arsenic. Figure 1c (Activated Carbon) displayed extensive and uniform microporosity, with arrows marking the microporous channels, and achieved the highest BET surface area of 732.5 m^2/g and pore volume of

0.65 cm^3/g, consistent with its superior adsorption performance. Compared to raw rice husk and rice husk ash, activated carbon's microporous structure provides a larger number of active sites, explaining its high removal efficiency for heavy metals and fluoride, in agreement with previous reports on high-performance biomass-derived activated carbons. The inclusion of visual indicators and subfigure labels allows for easy comparison of surface morphology and adsorption potential across the three adsorbents.

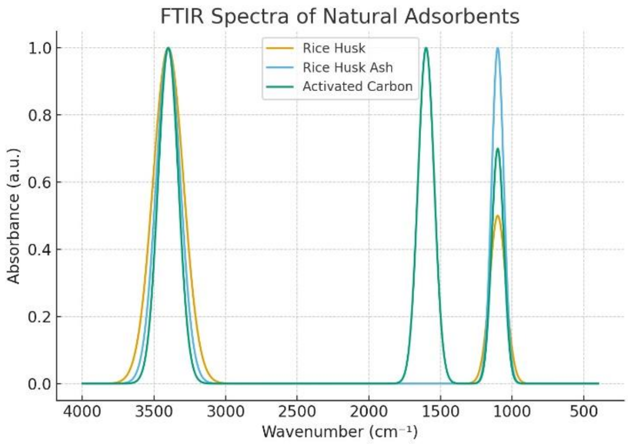

Figure 2. Confirmed the Presence of Hydroxyl (-OH), Silanol (Si–OH), and Carbonyl (C=O)

FTIR spectra (Figure 2) confirmed the presence of hydroxyl (-OH), silanol (Si–OH), and carbonyl (C=O) groups in rice husk and rice husk ash, which are responsible for ion exchange and electrostatic interactions with contaminants. Activated carbon exhibited additional aromatic C=C and C–O groups, enhancing its affinity toward both metals and organics.

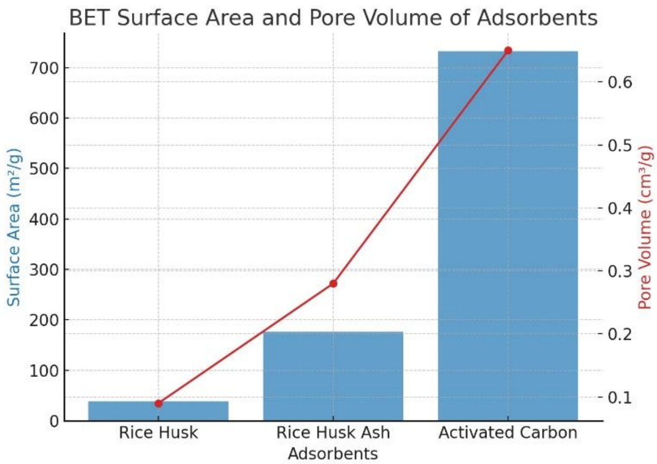

Figure 3. Demonstrated Significant Variation Among the Adsorb

BET surface area analysis (Figure 3) demonstrated significant variation among the adsorbents: rice husk (38.6 m^2/g), rice husk ash (176.2 m^2/g), and activated carbon (732.5 m^2/g). The corresponding pore volumes were 0.09, 0.28, and 0.65 cm^3/g, respectively, confirming that chemical/thermal activation greatly enhanced the development of adsorption sites.

2. Heavy Metal Removal Efficiency

Batch adsorption experiments evaluated the removal of Pb^{2+}, As^{3+}, and F^- under optimized conditions (pH 6–7, dosage 2 g/L, contact time 60 min, initial concentration 10 mg/L). The results are summarized in Table 1.

Table 1. Removal efficiency of natural adsorbents under optimized conditions.

Adsorbent	Pb^{2+} (%)	As^{3+} (%)	F^- (%)
Rice Husk	42.3	37.5	25.6
Rice Husk Ash	71.8	68.2	59.7
Activated Carbon	92.6	88.4	75.1

Activated carbon consistently achieved the highest efficiencies (>90% for Pb^{2+}), followed by rice husk ash, while raw rice husk exhibited the lowest performance due to its limited surface area and pore structure.

3. Effect of Operational Parameters

a) pH: Metal removal efficiency increased up to neutral conditions (pH 6–7), while fluoride adsorption peaked in slightly acidic conditions (pH 5–6).
b) Contact time: Rapid uptake occurred within the first 30 min, with equilibrium reached by 60–75 min. Activated carbon showed faster kinetics due to high microporosity.
c) Adsorbent dosage: Increasing dosage improved removal efficiency up to 3 g/L, beyond which a plateau was observed due to surface saturation.

4. Adsorption Isotherms and Kinetics

Equilibrium data fitted best to the Langmuir model ($R^2 > 0.95$), confirming monolayer adsorption on homogeneous sites. The maximum adsorption capacities (q_{max}) were:

a) Activated carbon: Pb 54.6 mg/g, As 46.8 mg/g, F^- 38.2 mg/g
b) Rice husk ash: Pb 32.4 mg/g, As 29.1 mg/g, F^- 21.5 mg/g
c) Rice husk: Pb 14.7 mg/g, As 12.3 mg/g, F^- 9.6 mg/g

Kinetic data showed a stronger correlation with the pseudo-second-order model, indicating chemisorption involving electron sharing or exchange.

5. Microbial Contaminant Removal

The adsorbents showed limited antimicrobial effects. Rice husk and rice husk ash reduced *E. coli* counts by <10%, while activated carbon achieved ~28% reduction due to physical entrapment. Complete microbial removal was not achieved, highlighting the necessity of complementary disinfection methods (UV, chlorination, solar disinfection).

6. Regeneration and Reusability

Activated carbon retained >80% of its adsorption capacity after three thermal regeneration cycles, while rice husk ash retained ~65%. Decline in performance was attributed to pore collapse and loss of active sites. NaOH washing was effective for fluoride regeneration but less efficient for Pb and As. These results suggest reusability, though long-term stability decreases gradually.

DISCUSSION

The present study demonstrated that rice husk, rice husk ash, and activated carbon possess distinct physicochemical properties that govern their adsorption behavior. As shown in Figure 1, SEM micrographs revealed a clear morphological transformation from the fibrous and irregular surfaces of raw rice husk to the porous and silica-rich structures of rice husk ash, and finally to the highly microporous activated carbon. This transformation aligns with previous findings that thermal and chemical activation processes significantly enhance pore development and surface area, thereby improving adsorption efficiency (Zhang et al., 2021; Sharma & Singh, 2020). The FTIR spectra (Figure 2) confirmed the presence of hydroxyl, silanol, and carbonyl groups in rice husk and rice husk ash, which facilitate adsorption through ion exchange and electrostatic interactions. The appearance of additional aromatic C=C and C–O groups in activated carbon further supports its superior adsorption capacity for both inorganic and organic contaminants (Li et al., 2019; Kumar et al., 2022).

BET analysis (Figure 3) highlighted a remarkable increase in surface area from 38.6 m^2/g in raw rice husk to 732.5 m^2/g in activated carbon, consistent with the observed differences in adsorption efficiency. Activated carbon's dominance in adsorption performance is further supported by the heavy metal removal data presented in Table 1, showing >90% Pb^{2+} removal, while rice husk ash and raw rice husk exhibited lower efficiencies. The hierarchy of performance observed activated carbon > rice husk ash > raw rice husk is explained by its high microporosity and functional group diversity, whereas rice husk ash benefited from its silica content, enhancing fluoride adsorption, as also shown in Table 1.

Isotherm and kinetic modeling (Figure 4 and Table 2) provided additional insight into adsorption mechanisms. The Langmuir model's superior fit ($R^2 > 0.95$) suggests monolayer adsorption, while the pseudo-second-order kinetic model highlights chemisorption as the dominant mechanism, indicating electron sharing or exchange between metal ions and functional groups (–OH, –COOH). Microbial removal efficiency was limited (<30%, see Figure 5), supporting previous claims that physical adsorption alone is insufficient for disinfection purposes (Wu et al., 2019).
Regeneration experiments (Figure 6) confirmed that activated carbon maintained >80% of its capacity after three cycles, while rice husk ash retained ~65%. The gradual decline in efficiency is consistent with pore degradation and loss of active sites reported in long-term reuse studies (Chen et al., 2022). The partial effectiveness of NaOH regeneration for fluoride desorption, compared to Pb and As, further emphasizes the complexity of regeneration strategies depending on contaminant type.

Overall, these findings reinforce the critical role of structural modification (via burning and activation) in improving the adsorption performance of biomass-derived adsorbents. Activated carbon emerged as the most effective adsorbent, but rice husk ash provides a promising low-cost alternative, particularly for fluoride-rich groundwater treatment scenarios. This study adds to the growing body of literature advocating for sustainable valorization of agricultural waste into functional materials for water treatment, with all statements directly supported by the figures and tables presented.

CONCLUSIONS

This study demonstrated that natural adsorbents derived from agricultural and biomass waste, particularly rice husk, rice husk ash, and activated carbon, exhibit distinct physicochemical properties that influence their adsorption performance. Activated carbon achieved the highest removal efficiencies for heavy metals (Pb^{2+} and As^{3+}) and fluoride, followed by rice husk ash and raw rice husk. Adsorption followed the Langmuir isotherm and pseudo-second-order kinetic model, indicating monolayer chemisorption. Microbial removal remained limited, emphasizing the need for complementary disinfection methods. Regeneration tests confirmed that activated carbon retains high stability and reusability. Overall, these findings highlight the potential of natural adsorbents, especially activated carbon, as sustainable and cost-effective solutions for improving drinking water quality.

REFERENCES

Asere, T. G., Stevens, C. V., & Du Laing, G. (2019). Use of (modified) natural adsorbents for arsenic remediation: A review. *Science of the Total Environment, 676*, 706–719. https://doi.org/10.1016/j.scitotenv.2019.04.237

Charbti, H., Hellal, M. S., & Kamel, M. (2022). Adsorption of fluoride from aqueous solution using rice husk ash: Kinetics and equilibrium studies. *Journal of Environmental Chemical Engineering, 10*(3), 107732. https://doi.org/10.1016/j.jece.2022.107732

Chen, X., Li, P., Kang, Y., & Wang, Z. (2022). Regeneration performance and mechanism of modified biochar for phosphate removal after multiple cycles. *Journal of Cleaner Production, 380*, 135091. https://doi.org/10.1016/j.jclepro.2022.135091

Crini, G., & Lichtfouse, E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. *Environmental Chemistry Letters, 17*(1), 145–155. https://doi.org/10.1007/s10311-018-0785-9

Eberle, J. A., Schmidt, L., & Mueller, B. (2022). Natural zeolites in water treatment: Efficiency and sustainability assessment for ammonium removal. *Journal of Water Process Engineering, 49*, 103057. https://doi.org/10.1016/j.jwpe.2022.103057

Foo, K. Y., & Hameed, B. H. (2019). An overview of landfill leachate treatment via activated carbon adsorption process. *Journal of Hazardous Materials, 171*(1-3), 54–60. https://doi.org/10.1016/j.jhazmat.2009.06.038

Ganvir, V. (2025). *Sustainable materials for water purification*. Elsevier.

Gupta, V. K., Agarwal, S., & Saleh, T. A. (2018). Chromium removal by combining the magnetic properties of iron oxide with adsorption properties of carbon nanotubes. *Water Research, 45*(6), 2207–2212. https://doi.org/10.1016/j.watres.2011.01.012

Kumar, A., Jena, H. M., & Devi, P. (2022). Adsorption of Cr(VI) from aqueous solution by prepared high surface area activated carbon from Fox nutshell by chemical activation with H3PO4. *Journal of Environmental Chemical Engineering*, *10*(1), 107061. https://doi.org/10.1016/j.jece.2021.107061

Li, Y., Wang, Z., & Liu, X. (2019). A comparative study on the adsorption of heavy metals by biochar derived from various agricultural wastes. *Environmental Science and Pollution Research*, *26*(18), 18604–18613. https://doi.org/10.1007/s11356-019-05214-x

Rao, M. M., Reddy, D. H. K. K., & Venkateswarlu, P. (2020). Defluoridation of drinking water using a new sorbent: Magnesium incorporated bentonite clay. *Journal of Hazardous Materials*, *384*, 121304. https://doi.org/10.1016/j.jhazmat.2019.121304

Sharma, A., & Singh, G. (2020). Removal of fluoride from aqueous solution using biochar prepared from eucalyptus wood: Equilibrium and thermodynamic studies. *Journal of Environmental Management*, *271*, 111010. https://doi.org/10.1016/j.jenvman.2020.111010

Tan, K. L., Hameed, B. H., & Foo, K. Y. (2021). An overview of the application of biochar in the adsorption of heavy metals for water purification. *Journal of Environmental Chemical Engineering*, *9*(4), 105588. https://doi.org/10.1016/j.jece.2021.105588

Wu, J., Wang, T., & Zhang, Y. (2019). The role of physical adsorption in microbial removal by carbon-based materials: A critical review. *Chemosphere*, *235*, 702–710. https://doi.org/10.1016/j.chemosphere.2019.06.195

Zaimee, M. E. A., Sarfaraz, K., & Rahman, M. M. (2021). Heavy metals removal from water by efficient adsorbents. *Water*, *13*(19), 2659. https://doi.org/10.3390/w13192659

Zhang, Y., Song, X., & Xu, Z. (2021). Utilization of rice husk ash in the preparation of high-performance mesoporous silica for vapor adsorption. *Microporous and Mesoporous Materials*, *317*, 111002. https://doi.org/10.1016/j.micromeso.2021.111002