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Fixed-Bed Column Performance of NaOH-Activated Hybrid Adsorbent Derived from Jengkol Peels and Coconut Shells for Cu(II) Removal

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Abstract
This study aims to evaluate the dynamic performance of NaOH-activated hybrid adsorbent derived from jengkol peels and coconut shell for Cu(II) removal in a fixed-bed column. The performance indicators include the adsorption capacity, removal efficiency, and structural characterization. The hybrid adsorbent was characterized using Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups that play a role in the adsorption process and Scanning Electron Microscope (SEM). The FTIR characterization results showed that the hybrid adsorbent was rich in functional groups such as hydroxyl (-OH), aromatic stretching (C=C), and aliphatic (C-H) groups. Meanwhile, the SEM characterization showed that the surface structure of the adsorbent tended to be honeycomb-shaped with varying pores. The adsorption test was performed in a downflow fixed-bed column under continuous operation with a total operation time of 30 minutes. Under the tested conditions (influent concentration of 100 mg/L and flow rate of 25 mL/min), 95% removal was achieved at 30 min in the fixed-bed column system, corresponding to a dynamic adsorption capacity of 11.3 mg/g. Kinetic modelling indicated that the Thomas and Yoon – Nelson models provided a better fit than the Adam-Bohart model, indicating that adsorption was primarily controlled by surface kinetics rather than intraparticle diffusion. This biomass waste-based hybrid adsorbent has the potential to be an environmentally friendly alternative for treating liquid waste containing Cu ions.

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INTRODUCTION

Copper (Cu) metal exposure arises from various activities, including mining, metal smelting and recycling, metal plating, electronics, pesticide-based agriculture, and corrosion of Cu water pipes. Copper waste that is not properly managed can accumulate in soil and water, is toxic, persistent, and bioaccumulates in the food chain because copper is a non-biodegradable metal (Liao et al., 2023). Based on Ministry of Environment Regulation No. 5 of 2014, the maximum limit for Cu contamination in industrial wastewater ranges from 0.8 to 3 mg/L depending on the industry category such as domestic wastewater quality standards, wastewater quality standards for businesses and/or activities polyethylene terephthalate industry, wastewater quality standards for businesses and activities caustic soda or chlorine industry specified in the regulation (MENLHK, 2014). In comparison, the World Health Organization (WHO) guideline value for Cu(II) is 2 mg/L, while the United States Environmental Protection Agency

(US EPA) sets an acceptable level of 1.3 mg/L for Cu in potable water (Al-Harby et al., 2024; Zeinali Heris et al., 2025).

Excessive exposure to Cu can cause health problems such as gastrointestinal irritation, liver and kidney damage, and oxidative stress. In an aquatic environment, increased of Cu concentrations may accumulate in biota and disrupt ecosystem balance (Qian et al., 2020). Chronic exposure in humans also carries the risk of triggering liver dysfunction and neurodegenerative diseases (Din et al., 2022), making Cu control very important.

One of the widely developed waste treatment technologies is adsorption using activated biomass adsorbents because it is efficient, environmentally friendly, and easy to operate (Sutama, Alfiana, et al., 2025). The adsorption process occurs through contact between wastewater and solid adsorbents, so that pollutants are absorbed on their surface (Lestari et al., 2022). The Coconut shells (*Cocos nucifera*) activated carbon is a commonly used biomass adsorbent because it has a high surface area and mechanical strength, a well-developed porous structure, and good chemical stability (Sujiono et al., 2022). In addition, local waste such as jengkol peels (*Pithecellobium jiringa*) has the potential to be used as a raw material for activated carbon because it contains high cellulose (57%) and a carbon content of around 40% (Mohadi et al., 2021). However, most studies have investigated these materials individually, and their combination remains largely unexplored.

The concept of hybrid adsorbents has emerged as a promising strategy to enhance the adsorption performance by integrating complementary physicochemical properties of different biomass sources. The hybrid adsorbent approach through the combination of several adsorbent materials is known to improve adsorption performance (Bissenova et al., 2025). Several studies show that hybrid adsorbents have high adsorption efficiency, such as sugarcane bagasse–banana stem hybrid adsorbents, which can remove methylene blue dye by up to 87% (Bakar et al., 2023), and N-CDs/$CuFe_2O_4$ adsorbents can remove Congo red dye by 85% (Zourou et al., 2024), as well as graphene carbonate sand composites that can remove heavy metals by up to 95% (Omdehghiasi et al., 2024).

Furthermore, chemical activation plays a crucial role in modifying surface functionality and porosity. Alkaline activation is known to enhance surface alkalinity, promote the formation of oxygen-containing functional groups, and improve metal ion affinity (Gao et al., 2020). Chemical activators such as NaOH and KOH are extensively utilized in the preparation of activated carbon due to their strong ability to modify surface functional groups and remove impurities that may block pore structures. Activated carbon treated with NaOH has been reported in some experiment exhibit a higher specific surface area compared to the other alkaline (Puspitasari et al., 2022). The smaller ionic radius of Na^+ compared to K^+ can facilitate deeper penetration into the carbon matrix, enhancing the formation of micropores while maintaining structural integrity

Most previous studies on Cu(II) removal have focused on batch adsorption systems and the use of single biomass-derived carbons. Although these studies provide important information on equilibrium capacity and adsorption mechanisms, limited attention has been given to the dynamic performance of hybrid biomass adsorbents in continuous fixed-bed column systems. In particular, studies examining NaOH-activated hybrid carbons derived from locally available agricultural waste in column configurations remain scarce.

Therefore, this study aims to determine the breakthrough characteristics and dynamic adsorption capacity of a NaOH-activated hybrid adsorbent prepared from coconut shell and jengkol peel for Cu(II) removal in a fixed-bed column system. The column approach was selected to better reflect practical operating conditions, where parameters such as influent concentration, flow rate, and bed configuration influence adsorption performance. This work provides initial insight into the feasibility of applying hybrid waste-based adsorbents in continuous

systems and supports the utilization of agricultural waste within a circular economy framework for sustainable wastewater treatment.

METHODS

1. Production of Hybrid Adsorbent

The jengkol (*Pithecellobium jiringa*) peels and coconut (*Cocos nucifera*) shells were washed with running water to remove dirt, then were dried in the sun for approximately 2 days. After that, the materials are further dried in an oven at 105°C for 12 hours. The dry materials are then carbonized using a furnace at 400°C for 2 hours to produce charcoal.

2. Chemical Activation of Adsorbent

The jengkol peels were carbonized, and the carbonized coconut shells were ground and sieved to 60 mesh. The mass ratio of 1:1 was based on the carbonized weight of each material. The two carbons were thoroughly homogenized before activation to ensure uniform mixing.

The hybrid mixture was co-activated by soaking in 0.1 M NaOH solution at a mass-to-volume ratio of 1:1 (g/mL) for 24 h in a static condition. After activation, the adsorbent was washed with distilled water until the filtrate pH reached 6.5-7.5. The hybrid adsorbent was then dried at 110 °C for 6 h to a constant weight and stored in an airtight container.

3. Adsorbent Characterizations

The surface functional groups of the adsorbent were analyzed using Fourier Transform Infrared (FTIR) in the wavenumber range of 4000–400 cm^{-1} using the KBr pellet method for sample preparation. Meanwhile, the surface morphology and pore structure of the adsorbent were observed using a Scanning Electron Microscope (SEM). Before analysis, the samples were sputter-coated with a thin layer of gold to minimize the charging effects, and the observations were conducted at an accelerating voltage of 15 kV.

4. Column System Adsorption Process

The solution of Cu(II) 100 mg/L was prepared from $CuSO_4 \cdot 5H_2O$ and flowed downwards through a column. The experiments were conducted using a cylindrical acrylic column with a total height of 50 cm, an inside diameter (ID) of 2 cm, and an outside diameter (OD) of 2.5 cm. The column was packed with 5 g of the hybrid adsorbent, and the adsorbent height was 4.5 cm, forming a fixed bed inside the column. A supporting sponge layer and a wire mesh were installed inside the column to hold the adsorbent and maintain stability during operation.

The Cu(II) solution was flowed at a constant flow rate of 25 mL/min using a peristaltic pump. Effluent samples were collected at 5-minute intervals. The residual Cu(II) concentration was analyzed using an Atomic Absorption Spectrophotometer (AAS) to observe the decrease in Cu(II) concentration. The fixed-bed configuration was employed to simulate continuous operating conditions and to evaluate the dynamic adsorption performance.

5. Adsorption Efficiency

Adsorption efficiency is the ability of an adsorbent to remove adsorbate from a solution, which is determined based on the decrease in adsorbate concentration between the influent and effluent. Adsorption efficiency in a continuous process can be seen from the dynamic adsorption capacity determined from eq.1.

$$q_{dyn} = \frac{Q}{m}\int_0^t (C_0 - C_t)dt \quad (1)$$

Where q_{dyn} is the dynamic adsorption capacity (mg/g), Q is the volumetric flow rate (L/min), m is the mass of adsorbent (g), C_0 is the initial concentration of Cu (mg/L), C_t is the effluent concentration of Cu (mg/L), and t is the operation time (min).

Dynamic adsorption capacity is calculated as a cumulative value representing the adsorbent's capacity during a fixed-bed column operating condition (Matharage et al., 2025). Dynamic adsorption capacity is determined by integrating the difference in adsorbate concentration between the initial adsorbate or influent, C_0 (mg/L), and the adsorbate effluent at a certain time, Ct (mg/L), against the column operating time, t (min), then divided by the mass of adsorbent, m (gr). Dynamic capacity was computed using trapezoidal integration of discrete Ct data (Δt = 5 min).

The breakthrough data (C_T/C_0) obtained from the continuous adsorption experiments were fitted using three commonly reported kinetic models: the Thomas, Adams–Bohart, and Yoon–Nelson models (Table 1). These models were applied to evaluate the adsorption performance and to describe the dynamic behavior of Cu(II) removal in the fixed-bed column. The model parameters were determined by nonlinear regression analysis, and the suitability of each model was evaluated using the correlation coefficient (R^2).

Table 1. Kinetics model equation for a continuous adsorption system (Omitola et al., 2022)

Kinetic model	Linear Equation	Parameters
Thomas Constant	$\ln\left(\frac{C_0}{C_t}-1\right)=\left(\frac{K_{TH}q_0m}{Q}\right)-K_{TH}C_0t$	K_{TH} = Thomas rate constant (L/(mg.min) q_0 = maximum adsorption capacity of the adsorbent in the Thomas model(mg/g) m = mass of adsorbent (g) Q = volumetric flow rate (L/min)
Adams – Bohart	$\ln\left(\frac{C_t}{C_0}\right)=K_{AB}C_0t-\frac{K_{AB}N_0Z}{F}$	K_{AB}= Adams – Bohart rate constant (L/(mg.min) N_0 = adsorption capacity per unit volume of bed (mg/L) Z = Bed height (cm) F = linear flow velocity (cm/min)
Yoon – Nelson	$\ln\left(\frac{C_t}{C_0-C_t}\right)=K_{YN}t-\tau K_{YN}$	K_{YN}= Yoon – Nelson rate constant (1/min) τ = time required for 50% breakthrough (min)

Meanwhile, the percentage of adsorption is determined by dividing the difference between the initial adsorbate concentration, C_0 (mg/L), and the adsorbate at a certain time, Ct (mg/L), by the initial adsorbate concentration expressed as a percentage (%R) as stated in equation 2.

$$\%R=\frac{(C_0-C_t)}{C_0} \quad (2)$$

The removal percentage and dynamic adsorption capacity are then used to evaluate the performance of the adsorbent during the continuous adsorption process.

RESULTS AND DISCUSSION

1. Adsorbent Characterization

The characterization of adsorbents in this study was conducted to evaluate the surface functional groups and morphology or surface structure of adsorbents that play an important role in adsorbent performance. Variations in the FTIR spectrum are closely related to the chemical

composition of the raw material. Coconut shells are known to have a higher lignin content (45–50%) than jengkol peels, which range from 30–35% (Hayuni et al., 2022; Rahmawati et al., 2024). Jengkol peel also contains mostly natural phenolic compounds such as tannins, flavonoids, and oxygen-bound groups (Wartono et al., 2021). The higher lignin content plays a role in the formation of a more stable aromatic structure during pyrolysis, resulting in a stronger aromatic C=C band at around 1600 cm^{-1}.

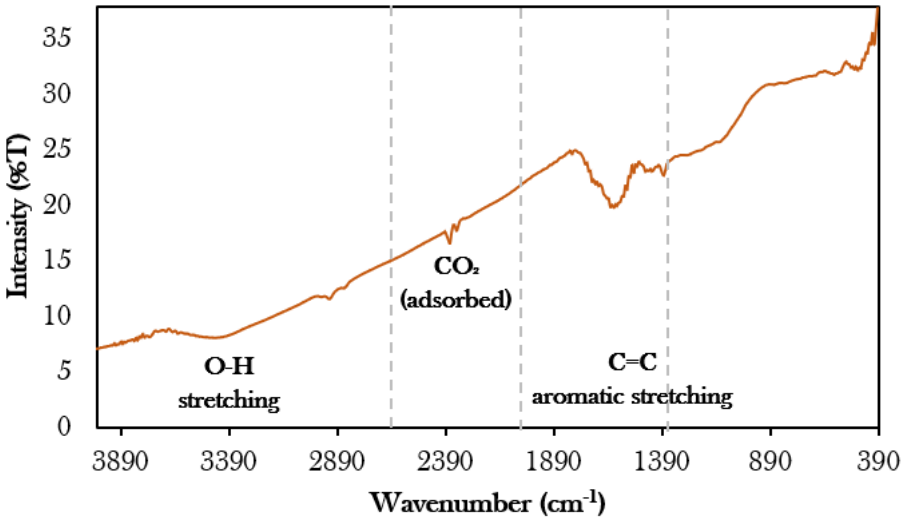


Figure 1. FTIR results of hybrid adsorbents

Figure 1 shows that the adsorbent has more than 5 peaks, which means that the sample is a complex molecule. There is a broad peak around the 3390 cm^{-1} area, followed by peaks appearing in the 1300–1600 cm^{-1} area, indicating the presence of hydrogen bonds and hydroxyl (-OH) groups. The narrow peaks below 3000 cm^{-1} indicate the presence of straight aliphatic chains. The presence of hydroxyl groups indicates dehydration and hydrogen bond breaking originating from the composition of raw materials such as cellulose, hemicellulose, and lignin (El Mahdaoui et al., 2024).

Peaks appearing at 2862.36 and 2924.09 cm^{-1} indicate the presence of aliphatic C-H stretching functional groups (Rahmat et al., 2025). Therefore, the small peaks appear around 1720 and 2850 cm^{-1}. These groups can be indicated as carbonyl in a small percentage, due to depolymerization or chain fragmentation, which means the breakdown of long chains of cellulose and hemicellulose that occurs at medium temperatures (Phothong et al., 2021). The small-intensity band observed in the 2330 – 2370 cm^{-1} region is attributed to the asymmetric stretching vibration of CO_2 molecules physically adsorbed on the porous surface of the hybrid activated carbon. This small peak indicated the physisorption within the pore structure that the presence of intrinsic functional groups in the carbon framework.

Moreover, the peak at a wavelength of 1597.06 cm^{-1} is more appropriately assigned to aromatic C=C stretching. This may also indicate the presence of amide or carboxylate groups (Putri et al., 2025). Meanwhile, the small peak that appears in the < 1500 cm^{-1} area is the fingerprint area. This area is possible due to the presence of aromatic structures on carbon or modifications to the carbon surface structure. The presence of aromatic structures identified through FTIR correlates with the formation of a relatively stable carbon framework, as seen in SEM analysis in the form of sturdy, layered pore walls.

In addition, activation with NaOH can easily remove lignin from the raw material, because the OH- ions in NaOH can weaken the lignin structure, allowing it to dissolve easily in water during the activation process (Wardani et al., 2020). Activation also causes carbon chain breakage, increases the porosity, and adds oxygen groups that enhance adsorptive properties. The FTIR analysis results are supported by the SEM analysis results in Figure 2.

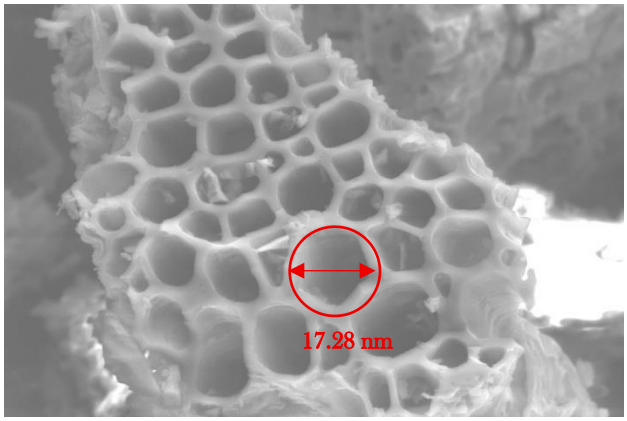


Figure 2. Morphological Structure of Hybrid Adsorbents

The results of morphological characterization of hybrid activated carbon using Scanning Electron Microscopy (SEM) at 3000x magnification show that the adsorbent has a rough and porous surface structure with interconnected macro-sized cavities. The pores visible on the activated carbon side vary in size and can be categorized as mesoporous pores with a size of 17.28 nm. This facilitates the diffusion of Cu ions into the pores (Almazoug et al., 2025). The honeycomb-like hollow structure indicates the formation of pores due to the carbonization and activation processes, which cause the degradation of lignocellulose components and the release of volatile substances (Haider et al., 2025). A large number of pores will increase the active pore surface area (Syukur et al., 2020).

2. Adsorption Efficiency

The adsorption efficiency in this study was conducted in a fixed-bed column with a continuous flow system. The dynamic adsorption capacity at t = 30 minutes obtained was 11.30 mg/g, illustrating the adsorbent's ability to accumulate Cu ions during the continuous adsorption process. This indicates that 1 g of hybrid adsorbent is capable of adsorbing approximately about 11 mg of Cu ions. The high dynamic adsorption capacity indicates a good affinity between Cu ions and the active sites of the adsorbent, and supports the effectiveness of the adsorbent in a continuous system.

Based on Table 2, the exhaustion condition (Ct/C0 ≈ 0.95) was not reached within the 30-minute experimental duration. This may be attributed to the relatively short operation time and the sufficient adsorption capacity of the 5 g adsorbent bed under the applied operating conditions (C_0 = 100 mg/L, Q = 25 mL/min). At this flow rate, the contact time between Cu(II) ions and the adsorbent was still adequate to maintain high removal efficiency, delaying the progression of the mass transfer zone toward the column outlet. Consequently, complete saturation of the bed did not occur during the tested period.

Table 2. Experimental Breakthrough Data for Cu Adsorption in a Fixed Bed-Column (Initial concentration of Cu is 100 mg/L)

Time (minute)	Effluent Concentration, C_T (mg/L)	C_T/C_0
5	48	0,48
10	47	0,47
15	36	0,36
20	20	0,20
25	7	0,07
30	5	0,05

The kinetic modeling results show that the experimental data were better fitted by the Thomas and Yoon–Nelson models compared to the Adams–Bohart model based on Table 3. This is indicated by the higher correlation coefficients obtained for the Thomas (R^2 = 0.9323) and Yoon–Nelson (R^2 = 0.9329) models, whereas the Adams–Bohart model showed a slightly lower value (R^2 = 0.9076). The Thomas model yielded an adsorption capacity (q_0) of 3.78 mg/g and a rate constant (K_{TH}) of 0.00132 L/(mg.min), indicating that the adsorption process follows typical fixed-bed behavior and is well described by Langmuir-type kinetic assumptions (Ng'ang'a et al., 2024). The Langmuir approach in adsorption assumes that the process occurs as monolayer adsorption on a homogeneous surface containing a finite number of identical active sites (Daffalla et al., 2022). Similarly, the Yoon–Nelson model provided a good prediction of the breakthrough profile, with K_{YN} of 0.132 1/min and τ of 7.57 min, representing the time required to reach 50% breakthrough (Omitola et al., 2022). The strong correlation with both kinetic models implies that the adsorption process is mainly controlled by surface interaction kinetics and the spatial distribution of active sites within the column, rather than being chiefly governed by intraparticle diffusion limitations. While the Adams–Bohart model is more limited to the initial adsorption stage.

Table 3. Comparison of kinetic models fitting in a continuous system

Thomas Constant				Adam-Boharts			Yoon-Nelson		
C_0 (mg/L)	q_0 (mg/g)	K_{Th} (L/(mg.min)	R^2	N_0 (mg/L)	K_{AB} (L/(mg.min)	R^2	K_{YN} (1/min)	τ (min)	R^2
100	3.78	0.00132	0.9323	0.87	0.001038	0.9076	0.132	7.57	0.9329

Figure 3 shows that there was a decrease in Cu concentration in the effluent, followed by an increase in the removal percentage to 95% at 30 minutes, indicating that the interaction between Cu ions and the adsorbent surface was effective (Sutama, Lestari, et al., 2025). A significant increase in removal percentage during longer operating times also indicates that the flow rate and mass of adsorbent used allowed sufficient contact time for the adsorption process to occur (Rivera-Arenas et al., 2023). Conversely, the decrease in the adsorbent's ability to adsorb Cu ions could be due to the interaction between the adsorbate (Cu^{2+}) and the functional groups on the adsorbent reaching the saturation point, resulting in desorption (Naat et al., 2021).

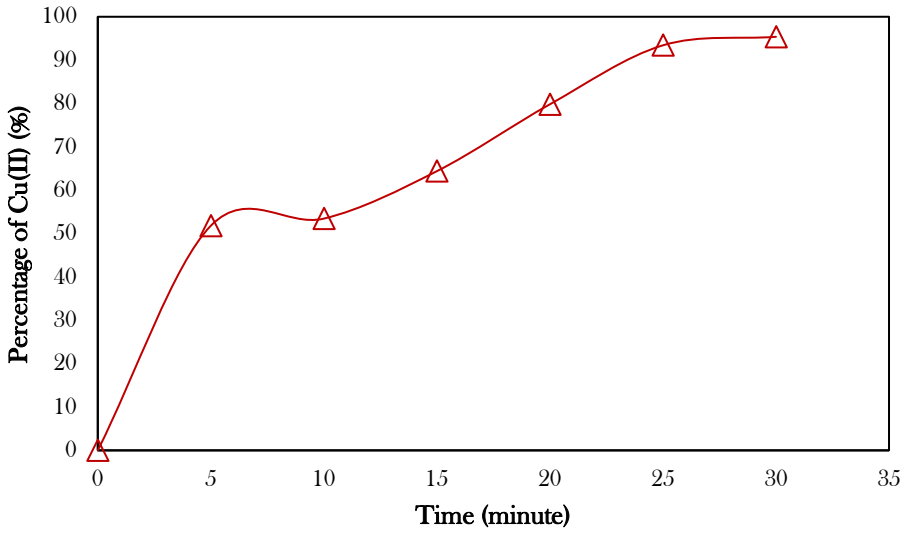


Figure 3. Percentage Removal of Cu(II) as a Function of Time

Therefore, this confirms that the applied operating parameters are capable of supporting the diffusion and attachment of Cu ions on the adsorbent surface optimally. Thus, the adsorbent used has the potential to be applied in wastewater treatment systems containing Cu ions continuously.

CONCLUSION

This study demonstrates that the hybrid adsorbent derived from jengkol peel and coconut shell effectively removes Cu(II) in a continuous fixed-bed column system. Under an influent concentration of 100 mg/L and a flow rate of 25 mL/min, the column achieved 95% removal efficiency within 30 minutes, corresponding to a dynamic adsorption capacity of 11.30 mg/g at the end of the operation period. Since bed exhaustion ($C_t/C_0 \approx 0.95$) was not reached, this value represents the adsorption capacity at 30 minutes rather than the maximum saturation capacity. The kinetics model fitted well with the Thomas constant and the Yoon–Nelson model. The removal performance reflects the synergistic contribution of the coconut shell, which enhances structural stability and pore development, and the jengkol peel, which provides oxygen-containing functional groups that promote interaction with Cu(II).

The adsorption process is likely influenced by a combination of physical adsorption within the porous structure and chemisorption through surface functional groups such as hydroxyl, aromatic stretching, and aliphatic groups. that facilitate complexation with Cu(II) ions. Although the results indicate promising performance under the tested conditions, further studies on complete breakthrough behavior, regeneration–reusability cycles, and application in real industrial wastewater are necessary to confirm the material's long-term feasibility and scalability.

REFERENCES (Baskerville Old Face 12pt; Bold; Left Aligned; UPPERCASE)

Al-Harby, N. F., Alrasheedi, M., Mohammed, A. elshifa M. E., Soliman, S. M. A., & Mohamed, N. A. (2024). Effective Removal of Cu(II) Ions from Aqueous Solution by Cross-Linked Chitosan-Based Hydrogels. *Water (Switzerland)*, *16*(16). https://doi.org/10.3390/w16162324

Almazoug, A. A., Mijatov, S., Vuksanović, M. M., Milosavljević, M., Mohammed, A. J. M., Milošević, M. D., Marinković, A., & Bartula, M. (2025). Sustainable Solutions for Pollutants Removal with a Hybrid Multifunctional Adsorbent Based on Recycled Expanded Glass. *Applied Sciences (Switzerland)*, *15*(6). https://doi.org/10.3390/app15063093

Bakar, A. A. A., Azmi, N. F. A. N., Daud, N. M., Ali, K. A. M., Badrealam, S., & Hamzah, N. (2023). The Removal of Dye from Synthetic Wastewater using Hybrid Modified Sugarcane Bagasse-Banana Stem. *IOP Conference Series: Earth and Environmental Science*, *1135*(1). https://doi.org/10.1088/1755-1315/1135/1/012010

Bissenova, M., Idrissov, N., Kuspanov, Z., Umirzakov, A., & Daulbayev, C. (2025). Hybrid adsorption–photocatalysis composites: a sustainable route for efficient water purification. *Materials for Renewable and Sustainable Energy*, *14*(2). https://doi.org/10.1007/s40243-025-00319-5

Daffalla, S. B., Mukhtar, H., Shaharun, M. S., & Hassaballa, A. A. (2022). Fixed-Bed Adsorption of Phenol onto Microporous Activated Carbon Set from Rice Husk Using Chemical Activation. *Applied Sciences (Switzerland)*, *12*(9). https://doi.org/10.3390/app12094354

Din, M. I., Khalid, R., Hussain, Z., Majeed, I., Najeeb, J., & Arshad, M. (2022). Preparation of activated carbon from Salvadora persica for the removal of Cu(II) ions from aqueous media. *Desalination and Water Treatment*, *266*, 131–142. https://doi.org/10.5004/dwt.2022.28641

El Mahdaoui, A., Radi, S., Elidrissi, A., Faustino, M. A. F., Neves, M. G. P. M. S., & Moura, N. M. M. (2024). Progress in the modification of cellulose-based adsorbents for the removal of toxic heavy metal ions. *Journal of Environmental Chemical Engineering*, *12*(5), 113870. https://doi.org/10.1016/j.jece.2024.113870

Gao, Y., Yue, Q., Gao, B., & Li, A. (2020). Insight into activated carbon from different kinds of chemical activating agents: A review. *Science of the Total Environment*, *746*, 141094. https://doi.org/10.1016/j.scitotenv.2020.141094

Haider, R., Sagadevan, S., Al-Adaileh, N., Fatimah, I., Paiman, S., Le, M. V., & Johan, M. R. (2025). Sustainable activated carbon derived from coconut shell and betel nuts for energy storage and environmental remediation. *Diamond and Related Materials*, *154*(12), 112243. https://doi.org/10.1016/j.diamond.2025.112243

Hayuni, S. N., Yeni Stiadi, & Emriadi, E. (2022). Pemanfaatan Ekstrak Lignin Dari Kulit Jengkol (Pithecellobium jiringa) Sebagai Inhibitor Korosi Baja Lunak Dalam Medium HCl. *Jurnal Kimia Unand*, *11*(2), 14–21. https://doi.org/10.25077/jku.11.2.14-21.2022

Kementerian Lingkungan Hidup Republik Indonesia. (2014). Peraturan Menteri Lingkungan Hidup Republik Indonesia. *Https://Jdih.Maritim.Go.Id/*, 1–83. https://jdih.maritim.go.id/en/peraturan-menteri-negara-lingkungan-hidup-no-5-tahun-2014

Lestari, D. I., Yuliansyah, A. T., & Budiman, A. (2022). Adsorption studies of KOH-modified hydrochar derived from sugarcane bagasse for dye removal: Kinetic, isotherm, and thermodynamic study. *Communications in Science and Technology*, *7*(1), 15–22. https://doi.org/10.21924/cst.7.1.2022.669

Liao, W., Zhu, Z., Feng, C., Yan, Z., Hong, Y., Liu, D., & Jin, X. (2023). Toxicity mechanisms and bioavailability of copper to fish based on an adverse outcome pathway analysis. *Journal of Environmental Sciences (China)*, *127*(5), 495–507. https://doi.org/10.1016/j.jes.2022.06.002

Matharage, H., Jayaweera, M., Bandara, N., Manatunge, J., Jayawardana, D., & Dissanayake, J. (2025). Fixed-bed column studies on the adsorption of bisphenol A from aqueous solutions using chemically activated king coconut biochar. *Discover Chemical Engineering*, *5*(1). https://doi.org/10.1007/s43938-025-00082-z

Mohadi, R., Palapa, N. R., Taher, T., Siregar, P. M. S. B. N., Normah, Juleanti, N., Wijaya, A., & Lesbani, A. (2021). Removal of Cr(VI) from aqueous solution by biochar derived from rice husk. *Communications in Science and Technology*, *6*(1), 11–17. https://doi.org/10.21924/CST.6.1.2021.293

Naat, J. N., Neolaka, Y. A. B., Lapailaka, T., Rachmat Triandi, T., Sabarudin, A., Darmokoesoemo, H., & Kusuma, H. S. (2021). Adsorption of Cu(II) and Pb(II) using silica@mercapto (hs@m) hybrid adsorbent synthesized from silica of Takari sand: Optimization of parameters and kinetics. *Rasayan Journal of Chemistry*, *14*(1), 550–560. https://doi.org/10.31788/RJC.2021.1415803

Ng'ang'a, N. S., Wanja, N. E., Nduta, W. R., & Mwangi, G. J. (2024). Fixed-Bed Column Adsorption Studies of Methylene Blue Dye from an Aqueous Solution Using Silicon Nitride Adsorbent Synthesized from Sand and Coffee Husk Wastes. *Progress in Chemical and Biochemical Research*, *7*(3), 283–292. https://doi.org/10.48309/pcbr.2024.446161.1343

Omdehghiasi, H., Yeganeh-Bakhtiary, A., & Korayem, A. H. (2024). Comprehensive study on copper adsorption using an innovative graphene carbonate sand composite adsorbent: Batch, fixed-bed columns, and CFD modeling insights. *Chemical Engineering and Processing - Process Intensification*, *206*(6), 110047. https://doi.org/10.1016/j.cep.2024.110047

Omitola, O. B., Abonyi, M. N., Akpomie, K. G., & Dawodu, F. A. (2022). Adams-Bohart, Yoon-Nelson, and Thomas modeling of the fix-bed continuous column adsorption of amoxicillin onto silver nanoparticle-maize leaf composite. *Applied Water Science*, *12*(5), 1–9. https://doi.org/10.1007/s13201-022-01624-4

Phothong, K., Tangsathitkulchai, C., & Lawtae, P. (2021). The analysis of pore development and formation of surface functional groups in bamboo-based activated carbon during co2

activation. *Molecules*, *26*(18). https://doi.org/10.3390/molecules26185641

Puspitasari, M., Nandari, W. W., & Hadi, F. (2022). Perbandingan Penggunaan Aktivator NaOH dan KOH pada Pembuatan Karbon Aktif dari Kulit Singkong (Manihot utilissima) Comparison of the Use of NaOH and KOH Activators in the Manufacture of Activated Carbon from Cassava Peel (Manihot utilissima). *Jurnal Teknik Kimia, Fakultas Teknik Industri, UPN "Veteran" Yogyakarta*, *19*(2), 58–62.

Qian, D., Xu, C., Chen, C., Qin, J. G., Chen, L., & Li, E. (2020). Toxic effect of chronic waterborne copper exposure on growth, immunity, anti-oxidative capacity and gut microbiota of Pacific white shrimp Litopenaeus vannamei. *Fish and Shellfish Immunology*, *100*(3), 445–455. https://doi.org/10.1016/j.fsi.2020.03.018

Rahmat, A., Zahrani, A., Hidayat, H., Arum, F., Respati, S. A., Susanti, W. D., Hariadi, H., & Mutolib, A. (2025). Characteristics of Jengkol Peel (Pithecellobium jiringa) Biochar Produced at Various Pyrolysis Temperatures for Enhanced Agricultural Waste Management and Supporting Sustainable Development Goals (SDGs). *ASEAN Journal of Science and Engineering*, *5*(1), 145–172. https://doi.org/10.17509/ajse.v5i1.81297

Rahmawati, A., Putri, F. A., & Dewati, R. (2024). *Pemanfaatan Lignin pada Tempurung Kelapa sebagai Alternatif Bahan Perekat Lignin Resorsinol Formaldehid (LRF)*. *13*(1), 73–78. https://doi.org/http://dx.doi.org/10.62870/jip.v13i1.25897

Rara Eka Dyla Putri, Dwi Indah Lestari, Debi Anggun Sari, Zeolita Prabu Putri, & Syariful Maliki. (2025). Potential of Biomass Raw Material for Biochar Production: A Review. *Chemical Engineering Journal Storage (CEJS)*, *5*(04), 528–553. https://doi.org/10.29103/cejs.v5i04.23084

Rivera-Arenas, D., Macías-Quiroga, I. F., Dávila-Arias, M. T., Vélez-Upegui, J. J., & Sanabria-González, N. R. (2023). Adsorption of Acid Yellow 23 Dye on Organobentonite/Alginate Hydrogel Beads in a Fixed-Bed Column. *Journal of Composites Science*, *7*(9). https://doi.org/10.3390/jcs7090362

Sujiono, E. H., Zabrian, D., Zurnansyah, Mulyati, Zharvan, V., Samnur, & Humairah, N. A. (2022). Fabrication and characterization of coconut shell activated carbon using variation chemical activation for wastewater treatment application. *Results in Chemistry*, *4*(11), 100291. https://doi.org/10.1016/j.rechem.2022.100291

Sutama, K., Alfiana, A. F., Rizkita, N., Lestari, D. I., & Aminah, S. (2025). Adsorption of Tofu Liquid Waste Using Rice Husk Activated Carbon. *Science Education and Application Journal*, *7*(1), 94–107. https://doi.org/10.30736/seaj.v7i1.1170

Sutama, K., Lestari, D. I., Endah, E., Wardani, K., Fauziah, S. M., & Alfiana, A. F. (2025). *Comparative Efficiency of KOH-Activated Rice Husk Carbon in Adsorbing Pollutants from Laundry and Tofu Wastewater*. *7*(2), 175–188.

Syukur, S., Anas, M., & Eso, R. (2020). Analisis Variasi Temperatur Aktivasi Terhadap Morfologi Permukaan Arang Aktif Tandan Aren (Arenga Pinnata MEER) Dengan Agen Aktivasi Potasium Silikat (K2SiO3). *Jurnal Penelitian Pendidikan Fisika*, *5*(3), 249. https://doi.org/10.36709/jipfi.v5i3.13979

Wardani, G. A., Nuramalia, L., Wulandari, W. T., & Nofiyantib, E. (2020). Utilization of Jengkol Peel (Pithecellobium jiringa (Jack) Prain) as Lead (II) Ions Bio-sorbent with Column Method. *Journal of Scientific and Applied Chemistry*, *23*(5), 160–166. https://doi.org/10.14710/jksa.23.5.160-166

Wartono, Mazmir, & Aryani, F. (2021). Analisis Fitokimia Dan Aktivitas Antioksidan Pada Kulit Buah Jengkol (Pithecellobium Jiringga). *Buletin Poltanesa*, *22*(1). https://doi.org/10.51967/tanesa.v22i1.472

Zeinali Heris, S., Pourpasha, H., Sagheb Asl, A., & Mohammadfam, Y. (2025). Efficient removal of copper ions from wastewater using a novel magnetic ZnO-MnFe2O4 decorated on MWCNTs adsorbent. *Journal of Molecular Liquids*, *437*(23), 128579.

https://doi.org/10.1016/j.molliq.2025.128579

Zourou, A., Ntziouni, A., Roman, T., Tampaxis, C., Steriotis, T., Gkouzia, G., Alff, L., Sanchez, D. E., Terrones, M., & Kordatos, K. V. (2024). Synthesis and characterization of magnetic carbon dots (CDs)-based hybrid material as an adsorbent for the removal of organic dye from water. *Carbon*, *230*(15), 119612. https://doi.org/10.1016/j.carbon.2024.119612