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Removal of COD, BOD, and Detergent from Laundry Wastewater Using Coconut-Shell Activated Carbon in Batch and Continuous Fixed-Bed Adsorption

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Abstract

Laundry wastewater contains high organic matter and detergent residues that may degrade the receiving water quality if discharged without treatment. This study investigated the performance of coconut-shell activated carbon for reducing chemical oxygen demand (COD), biochemical oxygen demand (BOD), and detergent concentration in laundry wastewater, using batch and continuous fixed-bed adsorption systems. Four activation treatments were evaluated at the batch stage: no activation, NaOH 0.2 N, HCl 0.1 N, and sequential NaOH 0.2 N–HCl 0.1 N. The best activator was then applied in a continuous upflow column with adsorbent thicknesses of 15, 20, and 25 cm. HCl 0.1 N produced the highest batch removal efficiencies, reaching 73.30% for COD, 71.53% for BOD, and 75.73% for detergent. Adsorption equilibrium for all parameters was better described by the Freundlich model than by the Langmuir model, indicating adsorption on a heterogeneous carbon surface. In the continuous system, the 25 cm bed showed the highest concentration-based removal, reaching 97.12% for COD, 97.03% for BOD, and 99.66% for detergent, and provided the longest breakthrough delay. However, the 20 cm bed yielded the highest average pollutant-load reduction, indicating a more balanced operational performance. Hydraulic conductivity decreased from 0.000058 to 0.000036 m/s during operation, suggesting progressive pore blockage and adsorbent saturation. These results demonstrate that coconut-shell activated carbon has good potential as a simple and practical adsorbent for decentralized laundry wastewater treatment.

Keywords: activated carbon, adsorption column, batch, detergent, laundry wastewater

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INTRODUCTION

Laundry wastewater has become an increasingly important source of urban water pollution due to the rapid growth of household and commercial laundry activities. This wastewater commonly contains detergents, surfactants, suspended solids, oils, phosphate compounds, and biodegradable as well as non-biodegradable organic matter, all of which may increase chemical oxygen demand

(COD), biochemical oxygen demand (BOD), foaming, nutrient enrichment, and oxygen depletion in receiving waters. In this study, the raw laundry wastewater contained COD of 350.66–450.21 mg/L, BOD of 127.55–190.75 mg/L, and detergent concentrations of 28.35–37.78 mg/L, indicating pollutant levels that required treatment before discharge.

Several treatment approaches have been developed for laundry wastewater, including coagulation, membrane filtration, electrochemical treatment, adsorption, biological treatment, and advanced oxidation. Earlier work showed that coagulation alone removed only 36% of COD and 51% of BOD, while the addition of granular activated carbon increased removal to approximately 93% for COD and 95% for BOD (Šostar-Turk et al., 2005). Electrocoagulation/electroflotation also reduced COD by about 62%, suggesting that electrochemical treatment can be effective but still requires electrical input and controlled operating conditions (Wang et al., 2009). Demonstration-scale treatment systems have also been explored for laundry wastewater reuse, but these studies focused more on overall system feasibility than on the specific role of adsorbent characteristics and column operation (Ciabatti et al., 2009). As summarized in **Table 1**, the treatment of laundry wastewater still requires simpler and more operationally practical systems that can reduce organic matter and detergent simultaneously.

Table 1. Comparison of previous studies on laundry wastewater treatment models, research design, and pollutant removal performance

Treatment Model	Research Design	Removal Capacity	Ref.
Coagulation + granular activated carbon/GAC + membrane filtration	• Laundry wastewater was treated using a multi-stage treatment approach. • The first stage applied coagulation/flocculation to reduce suspended and colloidal pollutants. • GAC adsorption was used as a polishing process to improve organic matter removal. • Membrane filtration was applied to further improve effluent quality for possible reuse. • The study focused on wastewater reclamation rather than adsorption-column optimization.	• Single coagulation: COD 36%; BOD 51%. • Coagulation + GAC: COD 93% and BOD 95%.	Šostar-Turk et al. (2005)
Purification and reuse system for laundry wastewater	• A demonstration-scale treatment system was developed for laundry wastewater purification and reuse. • The design was more application-oriented than conventional laboratory-scale experiments. • The system was tested under practical operating conditions. • The study emphasized water reuse feasibility rather than the individual adsorption performance of activated carbon.	• Specific removal efficiency for each pollutant was not clearly reported in the accessible source. • The study mainly emphasized system demonstration and reuse potential.	Ciabatti et al. (2009)
Electrocoagulation/ electroflotation	• Laundry wastewater was treated using an electrochemical process. • The study evaluated the effect of electrochemical operating conditions on COD reduction. • The process relied on coagulant generation and flotation through electrical current. • No adsorbent was used, making it a useful comparison with adsorption-based treatment.	• COD 62%.	Wang et al. (2009)

Treatment Model	Research Design	Removal Capacity	Ref.
Adsorption using polymer-supported hazelnut shell composites: PAn/HS and PPy/HS	• Commercial laundry wastewater was first pretreated by electrocoagulation. • Hazelnut shell-based adsorbents were modified with polyaniline and polypyrrole. • The adsorption process was optimized using Box–Behnken Design under Response Surface Methodology. • Operating variables included pH, contact time, adsorbent dosage, and mixing rate. • ANOVA and cost evaluation were used to assess process performance.	• PAn/HS: COD 75%. • PPy/HS: COD 52%. • Optimum PAn/HS condition: pH 8, adsorbent dosage 0.9 g/100 mL, mixing rate 125 rpm, and contact time 77.5 min.	Veli et al. (2019)
Coagulation, Fenton, photo-Fenton, biological filter, and GAC filtration	• • Several treatment processes were compared for hotel laundry wastewater. • The tested units included iron-salt coagulation, Fenton, photo-Fenton, biological filtration, and GAC post-treatment. • The research included process optimization, economic assessment, and life cycle assessment. • GAC was used as a polishing step after biological filtration when COD reduction was insufficient.	• Single biological filter: COD 80%, TP 42.3%. • Anionic and non-ionic surfactants: COD 100%. • BF + GAC reduced final COD to 103 mg/L.	Melián et al. (2023)
Batch adsorption using granular activated carbon and zeolite	• Real laundry wastewater was treated using GAC and zeolite as adsorbents. • The study used a batch adsorption system. • Adsorbent mass and contact time varied. • Adsorbent dosages of 4, 8, and 12 g were tested. • Contact time was evaluated up to 150 min. • Statistical analysis was used to determine optimum treatment conditions.	• Phosphate 60.71%. • COD 63.11%. • TSS 53.11%. • Adsorption capacity: phosphate 0.67 mg/g; COD 54.67 mg/g.	Nasir and Titah (2024)
Full-scale treatment system: thermophilic aerobic membrane reactor/TAMR + nanofiltration/NF + activated carbon/AC	• Real laundry wastewater was treated in a full-scale system. • Daily monitoring was conducted for more than three months. • The treatment train combined biological treatment, membrane separation, and activated carbon adsorption. • The study focused mainly on non-ionic and anionic surfactant removal. • Different treatment combinations were evaluated in terms of performance and operational cost.	• TAMR + NF + AC: total surfactant removal >95%. • MBAS removal >76%. • The study reported relatively high treatment cost per mass of surfactant removed.	Collivignarelli et al. (2019)
Solar photo-Fenton process at pilot-plant scale	• Laundry wastewater was treated using a solar photo-Fenton advanced oxidation process. • The process was operated at pilot-plant scale.	• COD 83%. • MBAS 96%.	García et al. (2021)

Treatment Model	Research Design	Removal Capacity	Ref.
	• Sodium dodecyl sulfate/SDS was used as a representative laundry surfactant. • The study evaluated the effect of water matrix and operational conditions on pollutant degradation. • The process was proposed as a post-treatment strategy for wastewater reuse.		
Combined biological process + advanced oxidation process	• A combined biological and advanced oxidation system was developed for on-site laundry wastewater reuse. • The biological stage used microbial adaptation to improve the degradation of detergent-related organic matter. • UV/O_3 was used as an advanced treatment step for residual detergent mineralization. • The study also evaluated treatment cost.	• Microbial adaptation: COD 91% at an F/M ratio of 0.12 gBOD/gMLSS·d. • UV/O_3 was reported to support complete mineralization of residual detergents. • Treatment cost: 0.65 €/m^3.	Benis et al. (2021)
MBBR + UV/O_3 oxidation + membrane separation	• Industrial laundry wastewater was treated using a hybrid system. • A moving bed biofilm reactor/MBBR was used as the main biological treatment unit. • Kaldnes K5 carriers were used as biofilm media. • MBBR effluent was further treated using UV/O_3, microfiltration, and nanofiltration. • The system was designed for the treatment and reuse of industrial laundry wastewater. • BOD, COD, surfactants, TOC, conductivity, and turbidity were evaluated.	• BOD 95–97%. • COD 90–93%. • Anionic and non-ionic surfactant 89–99%.	Mozia et al. (2020)

Recent studies (as shown in **Table 1**) have reported high pollutant removal by using combined treatment systems and advanced process configurations. Modified adsorbents, hybrid biological–oxidative systems, and membrane-based treatment trains have all shown strong performance for COD and surfactant removal. However, many of these approaches depend on multiple treatment units, membrane systems, advanced oxidation, biological acclimation, or comparatively complex operation. Such complexity may limit their applicability for small-scale and decentralized laundry wastewater treatment. Among the available approaches, adsorption remains attractive because it is simple, flexible, and suitable for decentralized applications.

Activated carbon is particularly promising due to its porous structure, high carbon content, and strong affinity for organic pollutants and surfactants (Anggriani et al., 2021; Arnelli et al., 2020; Winoto et al., 2020). Indonesia has abundant coconut-shell biomass, making coconut-shell activated carbon a locally relevant and potentially sustainable adsorbent for wastewater treatment. Compared with advanced oxidation, membrane separation, or biologically intensive systems, fixed-bed activated-carbon adsorption offers a simpler continuous-flow configuration because wastewater passes through a porous adsorbent bed without requiring membrane pressure, advanced oxidation control, or biological acclimation (Benis et al., 2021; Mozia et al., 2020; Melián et al., 2023). In this study, coconut-shell activated carbon was used as the adsorbent in the batch and continuous column systems.

Despite the practical advantages of adsorption, fewer studies have integrated activator selection, fixed-bed column operation, breakthrough behavior, pollutant-load reduction, and hydraulic conductivity within a single activated-carbon system for the simultaneous removal of COD, BOD, and detergent from laundry wastewater. The novelty of this study, therefore, lies in combining batch activator screening with continuous upflow fixed-bed evaluation using multiple performance indicators, including removal efficiency, adsorption isotherm, breakthrough characteristics, pollutant-load reduction, and hydraulic conductivity. Accordingly, this study aimed to evaluate the performance of coconut-shell activated carbon for simultaneous COD, BOD, and detergent removal from laundry wastewater, while identifying the most effective chemical activator and the most appropriate bed thickness under continuous operation.

METHOD

Materials and Laundry Wastewater Sampling

The materials used in this study were laundry wastewater, coconut-shell activated carbon (8 × 30 mesh), hydrochloric acid (HCl), sodium hydroxide (NaOH), distilled water, phenolphthalein indicator, methylene blue, chloroform, sulfuric acid (H_2SO_4), potassium dichromate, mercury sulfate ($HgSO_4$), silver sulfate (Ag_2SO_4), and potassium hydrogen phthalate. The main equipment included glass beakers, a magnetic stirrer, filter paper, an analytical balance, a porcelain cup, a crucible cup, a UV–Vis spectrophotometer, a pH meter, glass wool, and a bulb. All experiments and sample analyses were conducted at the Water Quality and Waste Management Laboratory, Faculty of Agro-industrial Technology and Biosystems, Universitas Brawijaya.

Laundry wastewater was used as the influent for both batch and continuous adsorption experiments. Wastewater was collected from a laundry facility located in Jatimulyo Village, Lowokwaru District, Malang, Indonesia, using a composite sampling method. Samples were stored in a storage container at approximately 4 °C before analysis. Initial wastewater characterization, including temperature, pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), and detergent concentration, was conducted using SNI standard methods. Separate wastewater samples were collected for the batch and continuous experiments on different sampling days to represent the influent condition of each experimental stage. The resulting values were compared with East Java Governor Regulation No. 52 of 2014 concerning wastewater quality standards for industrial and other business activities (Pemerintah Provinsi Jawa Timur, 2014).

Activated-carbon Preparation and Characterization

Coconut-shell activated carbon with a particle size of 8 × 30 mesh (approximately 0.60–2.36 mm) was used as the adsorbent in this study. For clarity, this size corresponds approximately to a particle diameter range of 0.6–2.4 mm. The activated carbon was prepared under four activation conditions: no activation, NaOH 0.2 N activation, HCl 0.1 N activation, and sequential NaOH 0.2 N–HCl 0.1 N activation. Chemical activation was performed by soaking the activated carbon in the respective activator solution. For NaOH activation, the carbon was immersed in NaOH 0.2 N for 18 h, whereas for HCl activation, the carbon was immersed in HCl 0.1 N for 30 min. In the combined treatment, the carbon was first soaked in NaOH 0.2 N and subsequently treated with HCl 0.1 N. After activation, the carbon was filtered and washed with distilled water until a neutral pH was reached, then oven-dried at 105 °C before use.

The activated carbon was characterized by measuring water content and ash content as basic quality indicators. Water content was determined by heating 1 g of activated carbon in a pre-weighed porcelain cup at 110 °C for 3 h, followed by cooling in a desiccator and reweighing. Ash content was determined by heating 1 g of activated carbon in a pre-weighed crucible cup at 750 °C for 2 h, followed by cooling in a desiccator and weighing the remaining ash. The resulting values were compared with SNI 06-3730-1995 (Badan Standardisasi Nasional, 1995). In the present study, only basic physical characterization was conducted; therefore, additional analyses such as BET surface area, pore-size distribution, FTIR, SEM, iodine number, or point of zero charge were not available and should be considered in future work to better explain the adsorption mechanism.

Batch Adsorption Experiment

Batch adsorption was conducted as a preliminary screening stage to identify the most effective activation treatment before application in the continuous fixed-bed column system. Four adsorbent treatments were evaluated: non-activated carbon, NaOH 0.2 N-activated carbon, HCl 0.1 N-activated carbon, and sequential NaOH 0.2 N–HCl 0.1 N-activated carbon. For each run, 600 mL of laundry wastewater was placed in a glass beaker and contacted with 30, 60, 90, 120, and 150 g of activated carbon. The mixture was stirred at 100 rpm for 120 min using a magnetic stirrer, after which it was filtered using filter paper to separate the treated wastewater from the adsorbent. The filtrate was then analyzed for COD, BOD, and detergent concentration. Each treatment was performed in triplicate, and each parameter (COD, BOD, and surfactant) was measured three times. The mean value of the three measurements was used for subsequent data analysis. Removal efficiency was calculated using equation (1).

$$\text{Removal efficiency (\%)}: \frac{(C_0 - C_e)}{C_0} \times 100 \quad (1)$$

where C_0 is the initial concentration, and C_e is the final concentration after adsorption.
Adsorption capacity (equation (2)) was calculated using:

$$q_e = \frac{(C_0 - C_e) \times V}{m} \quad (2)$$

where q_e is the adsorption capacity (mg g^{-1}), V is the wastewater volume (L), and m is the adsorbent mass (g). The adsorption data were further fitted to the Freundlich in equation (3) and Langmuir in equation (4) isotherm models.

$$\text{Log } q_e = \log K_F + \frac{1}{n} \log C_e \quad (3)$$

$$\frac{C_e}{q_e} = \frac{1}{Q_{max} K_L} + \frac{C_e}{Q_{max}} \quad (4)$$

where K_F and n are Freundlich constants, while Q_{max} and K_L are Langmuir constants. In this study, isotherm fitting was used as an empirical approach to describe the adsorption tendency for COD, BOD, and detergent. The effects of activator variation on COD, BOD, and surfactant removal were analyzed separately using one-way analysis of variance (ANOVA) in SPSS at a significance level of 5%. When significant differences were detected, Honestly Significant Difference (HSD) post hoc analysis was applied to determine pairwise differences among treatments, and significance groupings were assigned accordingly. behavior.

Continuous Column Adsorption Experiment

The continuous adsorption experiment was conducted using the best activated carbon selected from the batch stage. Laundry wastewater was passed upward through a vertical fixed-bed adsorption column. The column was constructed from a 3-inch PVC pipe with an inner diameter of 8.6 cm and an outer diameter of 8.9 cm. The system consisted of a wastewater collection basin, a runoff basin, an influent basin, and an adsorption column, as shown in **Figure 1**. The activated-carbon bed thicknesses were 15, 20, and 25 cm, corresponding to adsorbent masses of 585, 791, and 997 g, respectively. The flow rate remained constant throughout the run. The activated carbon was pre-wetted or pre-washed before operation.

The cross-sectional area of the column was 0.00581 m^2, while the bed volumes for the 15, 20, and 25 cm columns were 0.871, 1.162, and 1.452 L, respectively. At the applied flow rate of 63.75 mL min^{-1}, the corresponding empty-bed contact times (EBCT) were 13.66, 18.23, and 22.78 min, respectively. The superficial velocity was approximately 1.83×10^{-4} m s^{-1}. Wastewater was pumped through the column using a Ginga GA-103 aquarium submersible pump, and the system was operated for 10 h. The flow rate remained constant throughout the run. The activated carbon was pre-wetted or pre-washed before operation.

Effluent samples were collected at 20, 40, 60, 120, 180, 240, 300, 360, 420, 480, 540, and 600 min and analyzed for COD, BOD, and detergent concentration. Breakthrough behavior was evaluated using the ratio C_e/C_0 as a function of time. In this study, the breakthrough point was defined as C_e/C_0 = 0.05, and column exhaustion as C_e/C_0 = 0.95, following commonly used criteria in fixed-bed adsorption analysis. The continuous column experiment was used to evaluate the effects of bed thickness on pollutant removal, breakthrough delay, pollutant load reduction, and hydraulic performance.

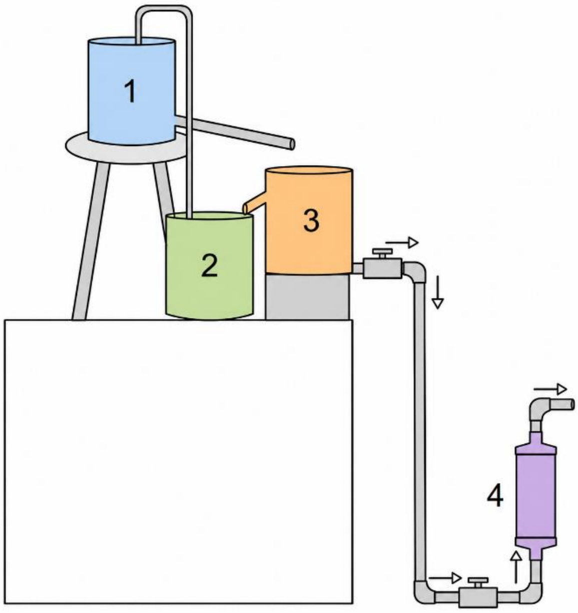

Figure 1. Adsorption column series for unit (1) Collection basin, (2) Runoff basin, (3) Influent basin, (4) Adsorption column

Pollution Load, Hydraulic Conductivity, and Data Analysis

Pollutant load was calculated to evaluate the amount of COD, BOD, and detergent remaining in the effluent during continuous column adsorption. Pollutant load was expressed in g s^{-1} and calculated using equation (5).

$$\text{Pollutant load} = Q \, x \, C \quad (5)$$

where C is the pollutant concentration (mg L^{-1}), and Q is the flow rate (L s^{-1}). Hydraulic conductivity was calculated to describe the ability of the activated-carbon bed to transmit wastewater during operation. The calculation followed Darcy's approach, as shown in equation (6).

$$K = \frac{(Q \times L)}{(A \times \Delta h)} \quad (6)$$

where K is hydraulic conductivity (m s^{-1}), Q is flow rate (m^3 s^{-1}), L is bed thickness (m), A is the column cross-sectional area (m^2), and Δh is the hydraulic head difference (m). In this study, the calculated decline in hydraulic conductivity was interpreted as evidence of increased flow resistance due to pollutant accumulation and progressive pore blockage within the adsorbent bed. The hydraulic conductivity values were calculated for a specific bed thickness.

Data analysis was performed using SPSS. The dataset was first checked to ensure consistency, completeness, and suitability for statistical processing. Outliers were inspected carefully, while retained values were kept when they reflected actual experimental variation. In the batch stage, the effect of activator type on COD, BOD, and surfactant removal was evaluated using one-way ANOVA, followed by HSD at a significance level of 5% when significant differences were observed. In the continuous stage, the effects of adsorbent thickness and adsorption time on COD, BOD, and surfactant concentrations were analyzed using factorial ANOVA, followed by HSD at the same significance level.

This step helped identify whether bed thickness and contact duration produced independent or combined treatment effects. The statistical outputs were then interpreted together with removal efficiency and breakthrough behavior. Pollutant-load reduction data were analyzed using the same statistical approach. Breakthrough curves were constructed by plotting C_e/C_0 versus time to determine the break point and exhaustion point for each bed thickness. In addition, a kinetic expression, $x = x_0 e^{-kt}$ was used to estimate the kinematic coefficient for COD, BOD, and surfactant removal at different adsorption times and bed thicknesses. These results supported model interpretation. This integration strengthened the reliability of adsorption performance evaluation in this study under varied operational treatment conditions.

RESULTS AND DISCUSSION

Characteristics of Activated Carbon and Initial Laundry Wastewater

The basic characteristics of the activated carbon were evaluated using water content and ash content, as summarized in **Table 2**. These parameters were used as initial indicators of adsorbent quality before it was applied for COD, BOD, and detergent removal. The water content ranged from 1.7% to 4.3%, with the highest value observed for non-activated carbon (4.3%) and the lowest for HCl 0.1 N-activated carbon (1.7%). Activated carbon treated with NaOH 0.2 N and sequential NaOH 0.2 N-HCl 0.1 N showed intermediate values of 2.8% and 2.1%, respectively. All treatments satisfied the maximum water-content requirement of 4.4% according to SNI 06-3730-1995 (Badan Standardisasi Nasional, 1995). A similar trend was observed for ash content. The highest ash content was found in non-activated carbon (2.5%), whereas HCl 0.1 N-activated carbon showed the lowest value (1.0%). The NaOH 0.2 N and sequential NaOH 0.2 N-HCl 0.1 N treatments produced ash contents of 1.6% and 1.2%, respectively, and all values also remained within the SNI maximum limit of 2.5%. These results indicate that HCl 0.1 N produced the most favorable basic adsorbent characteristics among the tested treatments. Lower water content is generally advantageous because excessive moisture may occupy pore spaces and reduce contact between adsorbate molecules and available adsorption sites, whereas lower ash content indicates fewer inorganic residues that may interfere with adsorption. However, these findings should be interpreted cautiously, since water and ash contents alone do not directly verify changes in surface area, pore structure, or surface chemistry.

Table 2. Characteristics of Activated Carbon under Different Chemical Activation Treatments

Activation treatment	Water content (%)	Ash content (%)	SNI 06-3730-1995 limit (Badan Standardisasi Nasional, 1995)
No activation	4.3	2.5	Water content: max. 4.4%; Ash content: max. 2.5%
NaOH 0.2 N	2.8	1.6	Water content: max. 4.4%; Ash content: max. 2.5%
HCl 0.1 N	1.7	1.0	Water content: max. 4.4%; Ash content: max. 2.5%
NaOH 0.2 N-HCl 0.1 N	2.1	1.2	Water content: max. 4.4%; Ash content: max. 2.5%

Table 3. Initial Characteristics of Laundry Wastewater

No.	Parameters	Initial Sample Characteristics		East Java Governor Regulation No. 52 of 2014 (Pemerintah Provinsi Jawa Timur, 2014)
		First Stage	Second Stage	
1.	Temperature (°C)	27	28	-
2.	pH	7.93	8.10	6.0-9.0
3.	COD (mg/L)	350.66	450.21	180
4.	BOD (mg/L)	127.55	190.75	75
5.	Detergent (mg/L)	28.35	37.78	3

The initial characteristics of the laundry wastewater used in the batch and continuous experiments are presented in **Table 3**. In the first-stage sample, the temperature, pH, COD, BOD, and detergent concentrations were 27 °C, 7.93, 350.66 mg/L, 127.55 mg/L, and 28.35 mg/L, respectively. In the second-stage sample, the corresponding values were 28 °C, 8.10, 450.21 mg/L, 190.75 mg/L, and 37.78 mg/L. The pH values in both stages were still within the permissible range of 6.0-9.0 based on East Java Governor Regulation No. 52 of 2014 (Pemerintah Provinsi Jawa Timur, 2014), whereas COD, BOD, and detergent concentrations all exceeded the discharge limits of 180 mg/L, 75 mg/L, and 3 mg/L, respectively. These results confirm that the raw laundry wastewater contained substantial organic and surfactant loads and therefore required treatment before discharge. Laundry wastewater commonly contains detergent residues, surfactants, oils, grease, suspended solids, and other washing additives that can increase COD and BOD levels (Herlambang & Hendriyanto, 2015).

Detergent compounds such as alkyl benzene sulfonate, linear alkylbenzene sulfonate, and sodium tripolyphosphate are difficult to degrade naturally and may contribute to foam formation and eutrophication when discharged into receiving waters. Direct discharge of untreated laundry wastewater may reduce water quality and disturb aquatic organisms due to oxygen depletion and chemical residue accumulation (Ardiyanto & Yuantari, 2016; Yusmidiarti, 2016).

The higher COD, BOD, and detergent values in the second-stage sample also show that laundry wastewater quality may vary between sampling times. Such variation is common because wastewater composition depends on detergent type, washing frequency, fabric load, and dilution level. Activated carbon is suitable for treating this wastewater because it has a porous structure, high carbon content, and strong capacity to adsorb organic compounds and surfactants (Anggriani et al., 2021; Fernianti et al., 2017). The data in **Table 3** provide the baseline condition for evaluating the effectiveness of activated carbon adsorption in reducing COD, BOD, and detergents from laundry wastewater.

Effect of Activation Treatment on COD, BOD, and Detergent Removal

The activation treatment clearly affected the ability of activated carbon to remove COD, BOD, and detergent from laundry wastewater, as shown in **Figure 2**. Non-activated carbon produced the lowest removal for organic indicators, with COD removal of 21.34% and BOD removal of 20.25%, although detergent removal reached 42.50%. This result indicates that untreated activated carbon still had adsorption ability, but its surface condition was less effective for reducing organic matter. Chemical activation improved adsorption performance in all cases. Activation with NaOH 0.2 N increased the removal efficiency to 43.98% for COD, 38.57% for BOD, and 44.31% for detergent. Further improvement was observed for the sequential NaOH 0.2 N-HCl 0.1 N treatment, which achieved removal efficiencies of 67.52% for COD, 63.31% for BOD, and 73.62% for detergent. The highest numerical removal efficiencies were obtained with HCl 0.1 N-activated carbon, reaching 73.30% for COD, 71.53% for BOD, and 75.72% for detergent. Statistical analysis confirmed that activator type significantly affected the removal of COD, BOD, and detergent (ANOVA, $p < 0.05$). Based on the HSD test, HCl 0.1 N gave the highest and significantly different COD and BOD removal and adsorption capacity compared with the other treatments, whereas for detergent removal, HCl 0.1 N and the sequential NaOH-HCl treatment fell within the same significance group, indicating statistically comparable performance for that parameter. Chemical activation is often associated with the removal of mineral impurities and the enlargement of pore structures, which supports higher adsorption capacity (Dewi et al., 2020; Lestari et al., 2016). Similar behavior was also reported by Martini and Yuliwati (2019), who stated that activation treatment can improve the performance of organic adsorbents by modifying surface characteristics and increasing active sites.

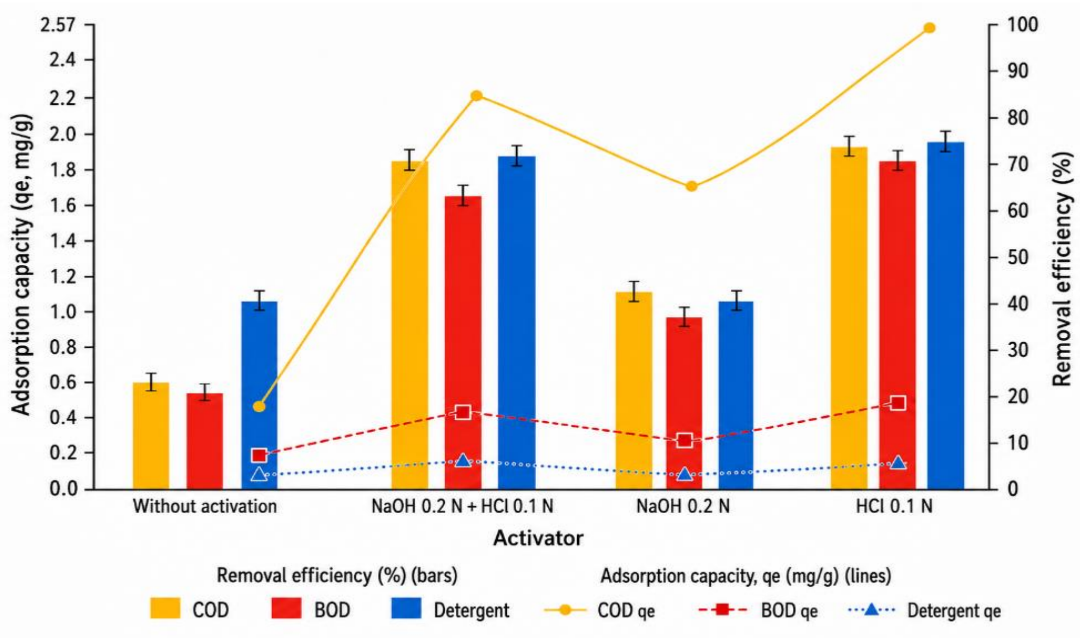

Figure 2. Effect of activated carbon activation treatment on COD, BOD, and detergent removal efficiency

The superior performance of HCl 0.1 N-activated carbon is consistent with the basic adsorbent characteristics presented in **Table 2**, where this treatment produced the lowest water content

(1.7%) and ash content (1.0%). Lower moisture and ash contents suggest fewer pore spaces occupied by water and fewer inorganic residues that may interfere with adsorption. Accordingly, the improved performance of HCl-activated carbon may be associated with cleaner and more accessible adsorption sites. Similar observations have been reported in previous studies, where acid activation improved the adsorption performance of carbonaceous materials by reducing residual impurities and enhancing adsorbent quality (Lestari et al., 2016; Martini and Yuliwati, 2019). The increased COD and BOD removal indicate more effective retention of dissolved and colloidal organic matter, whereas detergent removal reflects the adsorption of surfactant species that can interact with the carbon surface through hydrophobic and other weak surface interactions. Arnelli et al. (2020) explained that surfactant-related adsorption on activated carbon is strongly influenced by surface interaction and adsorbent modification. Based on its consistently high batch performance, HCl 0.1 N-activated carbon was selected for the subsequent continuous fixed-bed adsorption experiment. The results in **Figure 2** show that HCl 0.1 N was the most suitable activator for preparing activated carbon, 60 grams, in a batch experiment. This activator produced the best simultaneous removal of COD, BOD, and detergent and their adsorption capacity in the batch stage. Based on this performance, HCl 0.1 N-activated carbon was selected for the continuous column adsorption experiment. This selection was important because the continuous system required an adsorbent with stronger surface quality, lower impurity content, and higher pollutant retention capacity before being tested under different bed thicknesses and operating times.

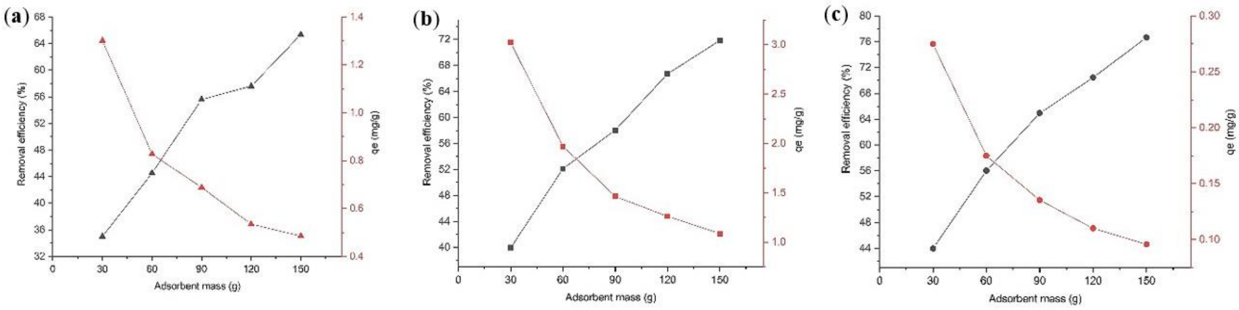

Figure 3. Removal efficiency (%) and adsorption capacity (qe, mg/g) for pollutant adsorption onto activated carbon: (a) BOD, (b) COD, (c) detergent.

Adsorption Capacity and Isotherm Model of COD, BOD, and Detergent Removal

The effect of adsorbent dose on pollutant removal efficiency and adsorption capacity is presented in **Figure 3**. For BOD, COD, and detergent, the removal efficiency increased progressively with increasing adsorbent mass from 30 to 150 g, whereas the adsorption capacity (q_e, mg/g) showed the opposite trend. This result indicates that a higher adsorbent dose provided a greater number of available adsorption sites and thereby enhanced overall pollutant removal, but the amount of pollutant adsorbed per unit mass of adsorbent decreased. Such behavior is commonly observed in batch adsorption systems, where increasing adsorbent dosage improves total uptake while lowering the specific adsorption capacity because the same pollutant load is distributed over a larger adsorbent mass. Activated carbon adsorption often involves pore filling, surface attraction, van der Waals interaction, and other weak physical interactions between adsorbate molecules and the adsorbent surface (Anggriani et al., 2021; Costa, 2019; Winoto et al., 2020). In the present study, the highest removal efficiencies were obtained at 150 g, reaching approximately 65.35% for BOD, 71.86% for COD, and 76.67% for detergent, whereas the highest $q_e$values were observed at 30 g, namely about 1.3006 mg/g for BOD, 3.0208 mg/g for COD, and 0.2748 mg/g for detergent. These results indicate a clear trade-off between maximizing overall removal and maximizing adsorption capacity per gram of activated carbon.

The adsorption behavior was further evaluated using the Freundlich and Langmuir isotherm models, as shown in **Figure 4a–f.** For COD adsorption, the Freundlich model produced an R^2value of 0.9397, which was substantially higher than that of the Langmuir model (0.5461). A similar pattern was observed for BOD, where the Freundlich model gave an R^2value of 0.9214 compared with 0.6271 for Langmuir. Detergent adsorption also followed the same trend, with the Freundlich model showing the highest R^2value (0.9607), while the Langmuir model produced only 0.5179. These results indicate that the Freundlich model provided a better empirical fit than the Langmuir model for all three parameters. The stronger Freundlich fit suggests adsorption on a heterogeneous activated-carbon surface with non-uniform adsorption energies and possible multilayer uptake, rather than ideal monolayer adsorption on identical sites. This interpretation is also consistent with the role of chemical activation, which can remove residual impurities, reduce pore blockage, and improve surface accessibility for pollutant retention (Dewi et al., 2020; Lestari et al., 2016). Similar improvements in adsorbent performance after activation have also been reported in wastewater-related adsorption systems, where better pollutant uptake was associated with cleaner surfaces and more accessible active sites (Veli et al., 2019).

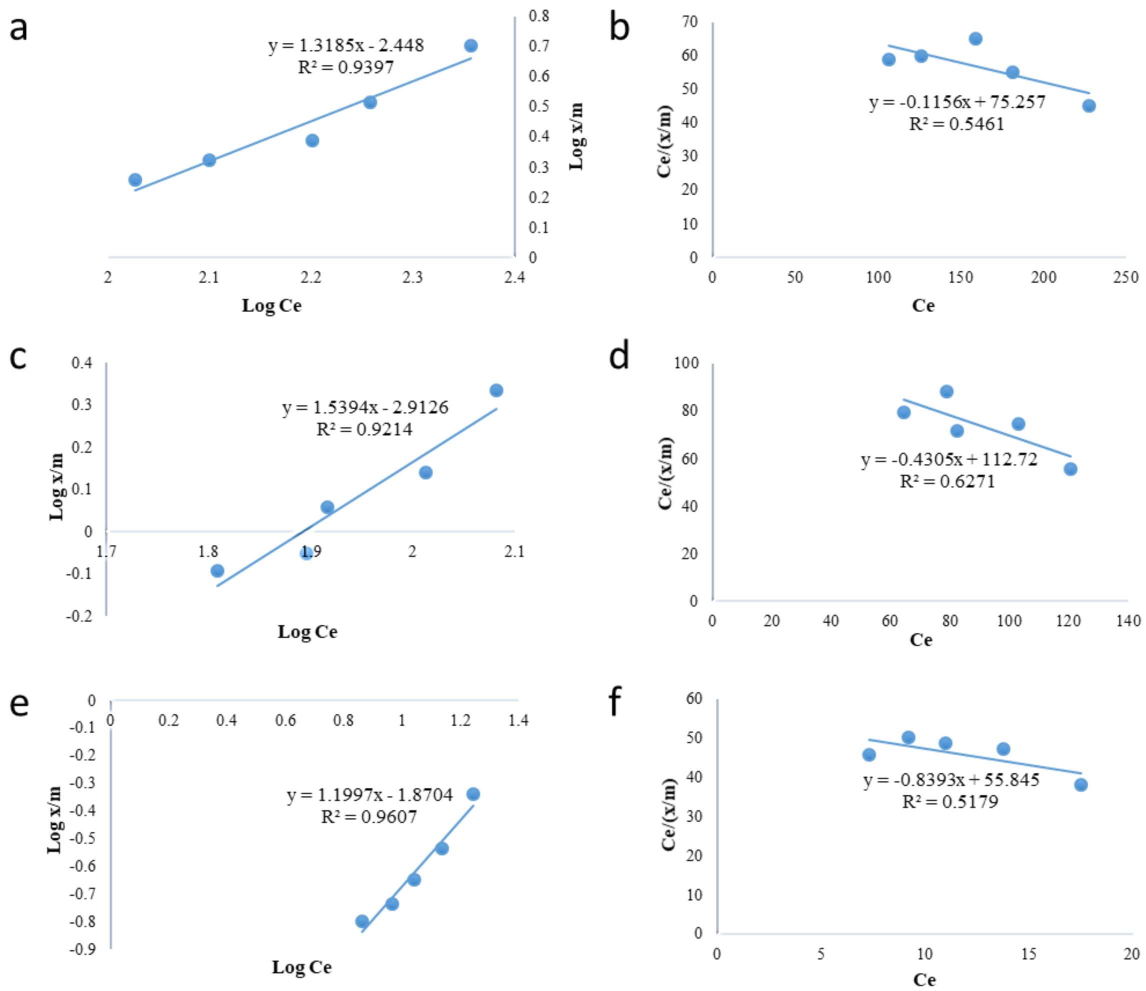

Figure 4. Freundlich and Langmuir isotherm models for pollutant adsorption onto activated carbon: (a) Freundlich model for COD, (b) Langmuir model for COD, (c) Freundlich model for BOD, (d) Langmuir model for BOD, (e) Freundlich model for detergent, and (f) Langmuir model for detergent

Accordingly, the Freundlich fit for COD and BOD should be understood primarily as an empirical description of overall adsorption tendency rather than strict proof of a single adsorption mechanism. For detergent, the stronger compatibility with the Freundlich model may reflect favorable interaction between surfactant molecules and the heterogeneous carbon surface, potentially through weak physical interactions and hydrophobic affinity between the surfactant tail and the adsorbent surface. Detergent adsorption may also involve hydrophobic interactions between surfactant tails and the carbon surface, while anionic surfactants can interact with hydrophobic adsorbent regions, which supports their retention inside carbon pores or on external surfaces (Arnelli et al., 2020). This interpretation is supported by previous studies on detergent-containing wastewater, where activated carbon and related adsorbents were effective for surfactant removal because of their porous structure and surface interaction capacity (Fernianti et al., 2017). Winoto et al. (2020) further reported that activated carbon can remove organic matter through its porous structure and large adsorption surface. The relatively poor Langmuir fit in **Figures 4b, 4d,** and **4f** further indicates that adsorption in this system was not adequately represented by uniform monolayer coverage. Overall, the results in **Figures 3** and **4** consistently support the selection of HCl 0.1 N-activated carbon for subsequent continuous-column experiments, because this adsorbent showed both strong removal performance and adsorption behavior consistent with heterogeneous surface uptake.

Continuous Column Adsorption Performance and Breakthrough Behaviour

The continuous fixed-bed column experiment was conducted to evaluate the effects of adsorbent thickness and operating time on COD, BOD, and detergent removal under flow conditions. As shown in **Figure 5a-c**, removal efficiency was highest at the beginning of operation and then decreased progressively with increasing adsorption time for all bed thicknesses, indicating gradual occupation of active sites during continuous use. Statistical analysis further confirmed that adsorbent thickness, adsorption time, and their interaction significantly affected COD, BOD, and detergent removal at a significance level of 5%. At 20 min, the 25 cm bed showed the highest concentration-based removal, reaching 97.12% for COD, 97.03% for BOD, and 99.66% for detergent, compared with 95.02%, 94.45%, and 98.01% for the 20 cm bed, and 94.56%, 94.11%, and 94.28% for the 15 cm bed, respectively.

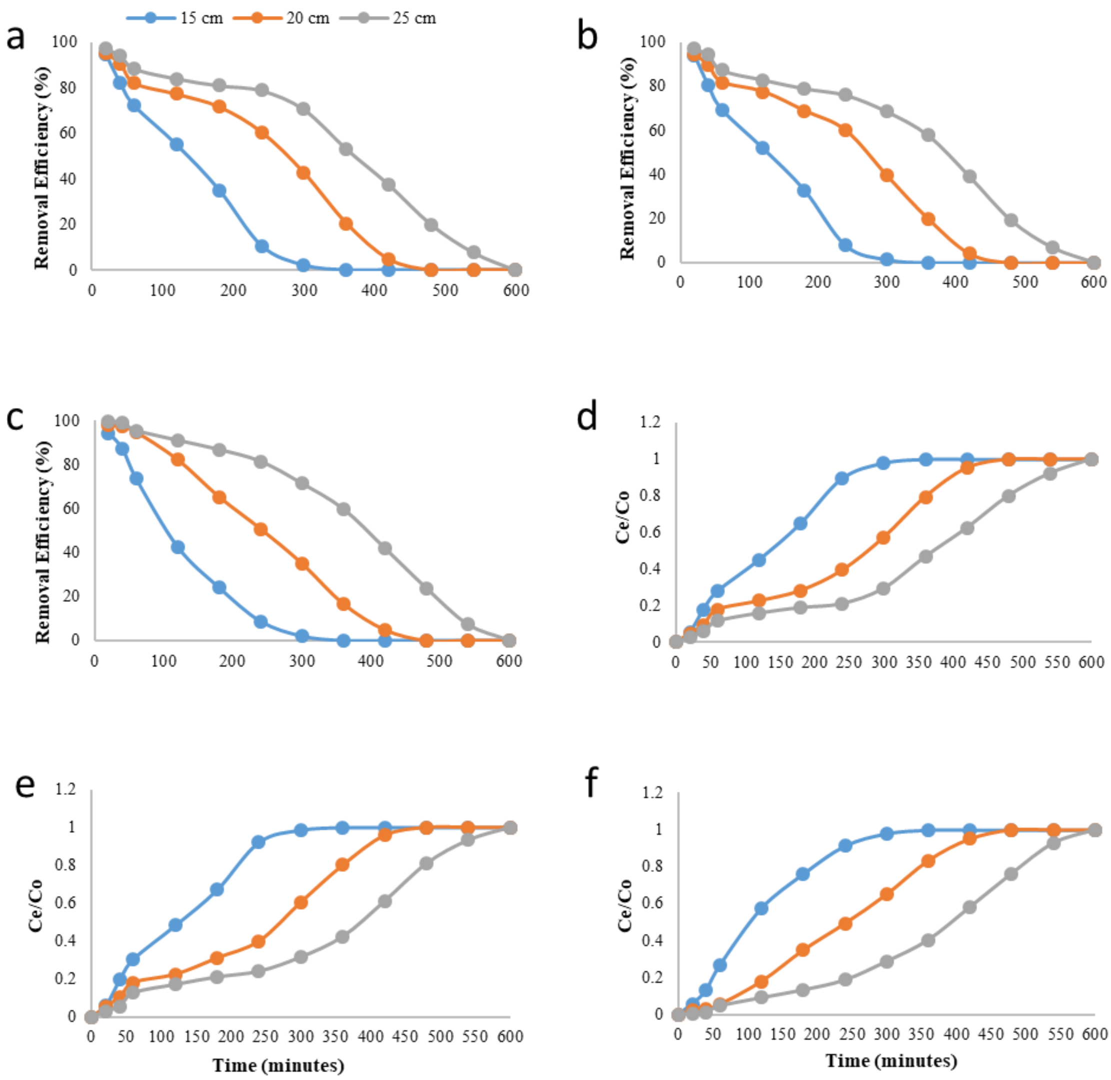

Figure 5. Effect of adsorbent thickness and contact time on pollutant removal and breakthrough behavior in activated carbon column adsorption: (a) COD removal efficiency, (b) BOD removal efficiency, (c) detergent removal efficiency, (d) COD breakthrough curve, (e) BOD breakthrough curve, and (f) detergent breakthrough curve.

These results indicate that a thicker activated carbon bed provided more available adsorption sites, a longer flow path, and greater contact time between wastewater and adsorbent, thereby enhancing short-term pollutant retention. For practical relevance, the effluent concentrations under the best short-term condition (25 cm bed at 20 min) were approximately 12.97 mg/L for COD, 5.66 mg/L for BOD, and 0.13 mg/L for detergent, all of which were below the applicable discharge limits. The role of bed depth in fixed-bed adsorption has also been reported in previous studies, where higher bed mass generally extends the adsorption zone and improves contaminant capture before saturation occurs (Mizwar, 2013; Costa, 2019). The decrease in removal efficiency after longer operation reflects the gradual occupation of active sites by organic matter and surfactant molecules. Activated carbon removes organic pollutants through pore filling, surface attraction, and weak intermolecular forces, while surfactant adsorption may involve hydrophobic interaction between carbon surfaces and the hydrocarbon chain of detergent molecules (Winoto et al., 2020; Arnelli et al., 2020).

The breakthrough profiles in **Figure 5d-f** provide a clearer picture of column saturation behavior. For COD and BOD, the 15 cm bed reached the break point at 20 min and the exhaustion point at about 5 h, while the 20 cm bed also reached the break point at 20 min but delayed exhaustion to about 7 h. The 25 cm bed showed the longest service time, with a break point at 40 min and exhaustion at about 10 h. For detergent, the 15 cm bed again reached the break point at 20 min and exhaustion at 5 h, whereas the 20 cm and 25 cm beds reached the break point at 60 min, with exhaustion at 7 h and 10 h, respectively.

The steeper breakthrough curves observed for the 15 cm bed indicate faster movement of the saturation front through the column, whereas the smoother and broader curves for the 25 cm bed suggest slower saturation and a wider mass-transfer zone. This behavior is consistent with fixed-bed adsorption theory, where deeper beds increase the available adsorption volume and delay the movement of the saturation front (Tuas, 2018). Pore structure also controls pollutant transport inside the adsorbent because accessible pores allow adsorbate molecules to reach internal active sites before leaving the column (Alimano & Syafila, 2014). Taken together, these results show that the 25 cm bed was the most effective in terms of concentration-based removal and breakthrough delay. However, the final selection of the most appropriate bed thickness should also consider pollutant-load reduction and hydraulic behavior, which are discussed in the following sub-section.

Pollution Load Reduction and Hydraulic Conductivity during Column Operation

Pollutant-load reduction was evaluated to determine the amount of COD, BOD, and detergent removed from laundry wastewater during continuous activated-carbon column operation. As shown in **Table 4**, the 20 cm bed produced the highest average pollutant-load reduction for all three parameters, reaching 0.000114 ± 0.000102 g/s for COD, 0.0000475 ± 0.0000428 g/s for BOD, and 0.0000096 ± 0.0000091 g/s for detergent. These results indicate that the highest concentration-based removal did not automatically yield the highest average pollutant-load reduction. This distinction is important because the 25 cm bed gave the lowest effluent concentrations and the longest breakthrough delay, whereas the 20 cm bed provided the most favorable average pollutant-load reduction.

The difference can be explained by the combined effects of bed thickness, effluent concentration, and hydraulic throughput. The 25 cm bed produced the smallest effluent concentrations but also the lowest column flow rate, while the 20 cm bed-maintained pollutant concentrations that were not markedly different yet allowed a higher flow rate than the 25 cm bed; consequently, the calculated pollutant load reduction became highest at 20 cm. Factorial ANOVA also showed that adsorption time, bed thickness, and their interaction significantly affected pollutant-load reduction for COD, BOD, and detergent. Therefore, the most balanced interpretation is that the 25 cm bed was most effective for concentration-based removal and breakthrough delay, whereas the 20 cm bed provided the highest average pollutant-load reduction and may represent the most balanced operational condition. Fixed-bed adsorption performance is strongly affected by bed depth, contact between adsorbate and adsorbent, and the movement of the mass-transfer zone through the column (Mizwar, 2013; Tuas, 2018). Adsorption also depends on pore accessibility and surface interaction between pollutant molecules and active sites (Alimano & Syafila, 2014). The 20 cm bed in this study appears to provide the most balanced condition for reducing COD, BOD, and detergent loads during continuous operation.

Table 4. Effect of adsorbent thickness on COD, BOD, and detergent pollution load reduction

No.	Thickness	Average (g/s)		
		COD	BOD	Detergent
1.	15 cm	0,000111 ± 0.000144	0,0000454 ± 0.0000600	0,0000089 ± 0.0000122
2.	20 cm	0,000114 ± 0.000102	0,0000475 ± 0.0000429	0,0000096 ± 0.0000092
3.	25 cm	0,000101 ± 0.000066	0,0000425 ± 0.0000277	0,0000090 ± 0.0000057

Hydraulic response was further considered because flow reduction can directly influence contact conditions, bed usability, and long-term treatment performance during operation. Hydraulic conductivity was evaluated for the 20 cm bed, which was selected for further operational interpretation based on pollutant-load reduction. As presented in **Table 5**, hydraulic conductivity decreased from 0.000058 m/s at 20 min to 0.000036 m/s at 600 min, with an overall value of 0.0000468 ± 0.0000070 m/s. This decline indicates progressive loss of flow capacity as adsorption proceeded. At the beginning of operation, the interparticle voids and internal pore channels were still relatively open, allowing wastewater to move more easily through the bed. With increasing operation time, however, organic matter, detergent residues, and other dissolved constituents were retained on the activated-carbon surface and within the pore network, thereby narrowing the available flow channels and increasing hydraulic resistance. This interpretation is consistent with the breakthrough curves, where the C_e/C_0 ratio increased with time for COD, BOD, and detergent, indicating progressive saturation of adsorption sites. In porous media, hydraulic conductivity is governed by the continuity of pore spaces and the ability of the medium to transmit water (Zendrato & Rusli, 2021; Annisa & Prijono, 2023). Therefore, the decrease observed here suggests increasing pore blockage and reduced internal accessibility during extended operation. Taken together, the pollutant-load and hydraulic-conductivity results show that column performance should be evaluated not only from removal efficiency but also from the balance between contaminant removal and hydraulic behavior over time.

Table 5. Hydraulic conductivity of the activated carbon column during continuous adsorption

No.	Time (minutes)	Hydraulic Conductivity (m/s)
1.	20	0,000058
2.	40	0,000055
3.	60	0,000053
4.	120	0,000053
5.	180	0,000049
6.	240	0,000048
7.	300	0,000045
8.	360	0,000044
9.	420	0,000041
10.	480	0,000040
11.	540	0,000039
12.	600	0,000036

CONCLUSION

Coconut-shell activated carbon effectively reduced COD, BOD, and detergent from laundry wastewater in both batch and continuous systems. In the batch stage, HCl 0.1 N was the best activator, achieving removal efficiencies of 73.30% for COD, 71.53% for BOD, and 75.73% for detergent. The adsorption data were better fitted by the Freundlich isotherm, indicating adsorption on a heterogeneous activated-carbon surface. In the continuous column system, the 25 cm bed gave the highest concentration-based removal and the longest breakthrough delay, reaching 97.12% COD, 97.03% BOD, and 99.66% detergent removal. However, the 20 cm bed showed the highest average pollutant-load reduction, with 0.000114 g/s for COD, 0.0000475 g/s for BOD, and 0.0000096 g/s for detergent, indicating the most balanced operational performance. Hydraulic conductivity decreased from 0.000058 to 0.000036 m/s, suggesting progressive pore blockage and adsorbent saturation. The main limitations of this study were the short operating period and the absence of regeneration, long-term stability, and economic evaluation. Future studies should therefore address regeneration cycles, scale-up, and techno-economic feasibility to support practical decentralized applications.

AUTHOR CONTRIBUTIONS

Conceptualization, ATSH and MK; methodology, ATSH, MK, and PS; software, ATSH and IFH; validation, MK, AE, and WP; formal analysis, ATSH, PS, and AG; investigation, ATSH, PS, AG, and IFH; resources, MK and AE; data curation, PS and AG; writing—original draft preparation, ATSH and PS; writing—review and editing, MK, AE, and WP; visualization, AG and IFH; supervision, MK, AE, and WP; project administration, MK; funding acquisition, ATSH and MK.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

REFERENCES

Alimano, M., & Syafila, M. (2014). Reduksi ukuran adsorben untuk memperbesar diameter pori dalam upaya meningkatkan efisiensi adsorpsi minyak jelantah. Jurnal Teknik Lingkungan, 20(2), 173–182. https://doi.org/10.5614/jtl.2014.20.2.8

Anggriani, U. M., Hasan, A., & Purnamasari, I. (2021). Kinetika adsorpsi karbon aktif dalam penurunan konsentrasi logam tembaga (Cu) dan timbal (Pb). Jurnal Kinetika, 12(2), 29–37. https://garuda.kemdiktisaintek.go.id/documents/detail/2140882

Annisa, D. W., & Prijono, S. (2023). Analisis konduktivitas hidrolik jenuh tanah pada berbagai jenis naungan di lahan kopi rakyat Kecamatan Sumbermanjing Wetan. Jurnal Tanah dan Sumberdaya Lahan, 10(1), 15–23. https://doi.org/10.21776/ub.jtsl.2023.010.1.2

Ardiyanto, P., & Yuantari, M. G. C. (2016). Analisis limbah laundry informal dengan tingkat pencemaran lingkungan di Kelurahan Muktiharjo Kidul Kecamatan Pedurungan Semarang. Jukung: Jurnal Teknik Lingkungan, 2(1), 1–12. https://doi.org/10.20527/jukung.v2i1.1055

Arnelli, Fazira, R., Astuti, Y., & Suseno, A. (2020). Synthesis of sodium lauryl sulfate (SLS) and hexadecyltrimethylammonium bromide (HDTMA-Br) surfactant-modified activated carbon as adsorbent for Pb^{2+} and NO_3^-. Jurnal Kimia Sains dan Aplikasi, 23(11), 396–402. https://doi.org/10.14710/jksa.23.11.396-402

Badan Standardisasi Nasional. (1995). SNI 06-3730-1995: Arang aktif teknis. Badan Standardisasi Nasional.

Benis, K, Z., Behnami, A., Aghayani, E., Farabi, S., & Pourakbar, M. (2021). Water recovery and on-site reuse of laundry wastewater by a facile and cost-effective system: Combined biological and advanced oxidation process. Science of the Total Environment, 789, 148068. https://doi.org/10.1016/j.scitotenv.2021.148068

Ciabatti, I., Cesaro, F., Faralli, L., Fatarella, E., & Tognotti, F. (2009). Demonstration of a treatment system for purification and reuse of laundry wastewater. Desalination, 245(1–3), 451–459. https://doi.org/10.1016/j.desal.2009.02.008

Collivignarelli, M. C., Carnevale Miino, M., Baldi, M., Manzi, S., Abbà, A., & Bertanza, G. (2019). Removal of non-ionic and anionic surfactants from real laundry wastewater by means of a full-scale treatment system. Process Safety and Environmental Protection, 132, 105–115. https://doi.org/10.1016/j.psep.2019.10.022

Costa, M. D. (2019). Studi penurunan kadar logam kromium (Cr) dalam limbah buatan elektroplating menggunakan metode presipitasi dan adsorpsi [Master's thesis, Institut Teknologi Sepuluh Nopember].

Dewi, R., Azhari, A., & Nofriadi, I. (2020). Aktivasi karbon dari kulit pinang dengan menggunakan aktivator kimia KOH. Jurnal Teknologi Kimia Unimal, 9(2), 12–22. https://doi.org/10.29103/jtku.v9i2.3351

Esteban García, A. B., Szymański, K., Mozia, S., & Sánchez Pérez, J. A. (2021). Treatment of laundry wastewater by solar photo-Fenton process at pilot plant scale. Environmental Science and Pollution Research, 28(7), 8576–8584. https://doi.org/10.1007/s11356-020-11151-x

Fernianti, D., Mardwita, & Suryati, L. (2017). Pengaruh jenis detergen dan rasio pengenceran terhadap proses penyerapan surfaktan dalam limbah detergen menggunakan karbon aktif dari ampas teh. Distilasi, 2(2), 10–14. https://doi.org/10.32502/jd.v2i2.1147

Herlambang, P., & Hendriyanto, O. (2015). Fitoremediasi limbah deterjen menggunakan kayu apu (Pistia stratiotes L.) dan genjer (Limnocharis flava L.). Jurnal Ilmiah Teknik Lingkungan, 7(2), 100–114. https://eprints.upnjatim.ac.id/7208/1/6._Prasetyo_dan_Okik.pdf

Lestari, R. S. D., Sari, D. K., Rosmadiana, A., & Dwipermata, B. (2016). Pembuatan dan karakterisasi karbon aktif tempurung kelapa dengan aktivator asam fosfat serta aplikasinya pada pemurnian minyak goreng bekas. Jurnal Teknika, 12(3), 419–430. https://jurnal.untirta.ac.id/index.php/ju-tek/article/view/6607

Martini, S., & Yuliwati, E. (2019). Pengaruh proses aktivasi terhadap kinerja adsorben organik dari kulit buah melon dalam menyerap ion logam Cr(III) dari limbah cair industri. Distilasi, 4(2), 33–40. https://jurnal.um-palembang.ac.id/distilasi/article/viewFile/3224/2262

Melián, E. P., Santiago, D. E., León, E., Reboso, J. V., & Herrera-Melián, J. A. (2023). Treatment of laundry wastewater by different processes: Optimization and life cycle assessment. Journal of Environmental Chemical Engineering, 11(2), 109302. https://doi.org/10.1016/j.jece.2023.109302

Mizwar, A. (2013). Penyisihan warna pada limbah cair sasirangan dengan adsorpsi zeolit dalam fixed-bed column. EnviroScienteae, 9(1), 1–9. https://doi.org/10.20527/es.v9i1.1979

Mozia, S., Janus, M., Bering, S., Tarnowski, K., Mazur, J., Szymański, K., & Morawski, A. W. (2020). Hybrid system coupling moving bed bioreactor with UV/O_3 oxidation and membrane separation units for treatment of industrial laundry wastewater. Materials, 13(11), 2648. https://doi.org/10.3390/ma13112648

Nasir, F. N., & Titah, H. S. (2024). The use of granular activated carbon and zeolite as an adsorbent to reduce the concentration of phosphate, chemical oxygen demand and total suspended solid in laundry wastewater. Journal of Ecological Engineering, 25(4), 170–183. https://doi.org/10.12911/22998993/184089

Pemerintah Provinsi Jawa Timur. (2014). Peraturan Gubernur Jawa Timur Nomor 52 Tahun 2014 tentang perubahan atas Peraturan Gubernur Jawa Timur Nomor 72 Tahun 2013 tentang baku mutu air limbah bagi industri dan/atau kegiatan usaha lainnya. Pemerintah Provinsi Jawa Timur.

Šostar-Turk, S., Petrinić, I., & Simonič, M. (2005). Laundry wastewater treatment using coagulation and membrane filtration. Resources, Conservation and Recycling, 44(2), 185–196. https://doi.org/10.1016/j.resconrec.2004.11.002

Tuas, M. A. (2018). Penurunan kadar logam tembaga dan besi pada limbah cair industri perhiasan emas menggunakan karbon aktif melalui proses presipitasi dan adsorpsi [Master's thesis, Institut Teknologi Sepuluh Nopember].

Veli, S., Arslan, A., Gülümser, Ç., Topkaya, E., Kurtkulak, H., Zeybek, Ş., Dimoglo, A., & İşgören, M. (2019). Advanced treatment of pre-treated commercial laundry wastewater by adsorption process: Experimental design and cost evaluation. Journal of Ecological Engineering, 20(10), 165–171. https://doi.org/10.12911/22998993/113136

Wang, C. T., Chou, W. L., & Kuo, Y. M. (2009). Removal of COD from laundry wastewater by electrocoagulation/electroflotation. Journal of Hazardous Materials, 164(1), 81–86. https://doi.org/10.1016/j.jhazmat.2008.07.122

Winoto, E., Hatina, S., & Sobirin. (2020). Pemanfaatan karbon aktif dari serbuk kayu merbau dan tongkol jagung sebagai adsorben untuk pengolahan limbah cair AAS. Jurnal Redoks, 5(1), 32–46. https://doi.org/10.31851/redoks.v5i1.4027

Yusmidiarti, Y. (2016). Analisis pengelolaan limbah cair usaha laundry. Jurnal Media Kesehatan, 9(1), 30–34. https://doi.org/10.33088/jmk.v9i1.289

Zendrato, T. M. K., & Rusli, H. A. R. (2021). Analisis perhitungan debit air tanah pada sistem penyaliran tambang terbuka di Pit X PT. Bukit Asam Tbk., Kabupaten Muara Enim, Provinsi Sumatera Selatan. Jurnal Bina Tambang, 6(5), 169–176. https://garuda.kemdiktisaintek.go.id/journal/view/1485?page=46