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Adsorption Isotherms and Kinetics of Heavy Metals Using H_3PO_4-Activated Carbon Derived from Oil Palm Fronds

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ABSTRACT

Toxic heavy metals in aquatic ecosystems pose serious environmental and ecological risks. This study evaluates the adsorption performance of H_3PO_4-activated oil palm frond biochar for removing Pb(II) and Cu(II) from a multi element system. Competitive adsorption was simulated using Certified Reference Material (CRM) containing 23 elements. The optimized adsorbent dosages were 0.05 g for kinetic experiments and 0.01 g for isotherm experiments, with metal concentrations of up to 10 mg/L in 25 mL of solution. Metal concentrations were analyzed using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES 5800 VDV). Kinetic analysis over 180 min showed that the adsorption process followed the pseudo-second order model, while equilibrium data were best described by the Langmuir isotherm, indicating selective adsorption toward competing metal ions. The adsorbent demonstrated high removal efficiencies for Fe, Al, Cu, Pb, and Cr, exceeding 80%. These results indicate that H_3PO_4-activated oil palm frond biochar has strong potential as an effective adsorbent for treating wastewater containing multiple hazardous heavy metals.

KEYWORDS: *Competitive Adsorption, Chemical Activation, ICP-OES, Isotherm, Kinetics.*

1. INTRODUCTION

Indonesia has approximately 9.2 million hectares of oil palm plantations [1]. This activity generates a substantial amount of solid biomass waste, one of which is oil palm fronds (Oil Palm Frond, OPF), with an estimated production of 4.5 million tons per year and a projected annual increase of 4% [2]. The lignin contents in the basal, middle, and apical sections of OPF from the Tenera variety were 20.7%, 18.95%, and 16.69%, respectively. The holocellulose contents were 81.57%, 80.33%, and 79.24%, while the α-cellulose contents were 44.57%, 43.56%, and 43.26%, respectively [3]. The utilization of OPF represents an effort to support the achievement of the Sustainable Development Goals (SDGs), particularly Goal 9 on industry, innovation, and infrastructure and Goal 12 on responsible consumption and production through the implementation of a circular economy.

The development of industrial and laboratory sectors has also increased the risk of wastewater discharge containing hazardous heavy metals, such as lead (Pb), copper (Cu), and aluminum (Al). Lead (Pb) is a potent neurotoxin, while high concentrations of copper (Cu) can be lethal to aquatic microorganisms. Although aluminum (Al) is generally considered less toxic than Pb, its ionic form can induce oxidative stress in aquatic organisms and cause long-term health effects [4]. Common wastewater treatment methods include neutralization, chemical precipitation, oxidation, reduction, adsorption, coagulation–flocculation, and biological treatment [5]. Environmental protection and management in Indonesia are regulated under Government Regulation No. 22 of 2021. However, the development of effective and efficient treatment technologies still requires further investigation, particularly for wastewater containing high concentrations of heavy metals.

Activated carbon is widely used as an adsorbent for water purification because of its relatively high surface area compared with other types of adsorbents. Furthermore, activated carbon can be produced from various organic and inorganic carbon-containing materials, with relatively simple chemical and physical activation processes [6]. Activated carbon derived from OPF and activated with phosphoric acid has a specific surface area of 376.4m²/g and exhibits a mesoporous structure [7]. A comparison of phosphoric acid and potassium hydroxide as activating agents showed that H_3PO_4 produced activated carbon with the lowest moisture content (1.4%), the lowest ash content (3.6%), the highest fixed carbon content (73.0%), and the highest iodine adsorption capacity (1699.2 mg/g). Therefore, H_3PO_4 was considered the more suitable activating agent [8]. The use of phosphoric acid promotes the cleavage of ether and ester bonds in OPF lingo cellulosic structures and facilitates cross-linking, thereby creating an extensive internal structure [9]. Phenolic and carbonyl groups interacting with phosphoric acid can form phosphorus-containing carbon species, such as C–O–P, which

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promote the formation of micro-pores and increase the surface area of activated carbon [10].

Chemical activation using 30% H_3PO_4 was followed by physical activation in a furnace at 500 °C. This activation process facilitates the development of pores on the activated carbon surface, while the presence of H_3PO_4 assists in promoting the cleavage and restructuring of ether and ester bonds [11]. Adsorption is a series of interactions between the surface of a solid material (adsorbent) and a contaminant (adsorbate), occurring in either liquid or gas phases [12]. The equilibrium relationship between the concentration of the adsorbate in the liquid phase and its concentration on the adsorbent particles at a given temperature determines the adsorption capacity of activated carbon [13].

$$qe = \left(\frac{Co-Ce}{w}\right) \times V \quad (1)$$

$$\%R = \left(\frac{Co-}{Co}\right) \times 100\% \quad (2)$$

Information:
q_e= adsorption capacity per unit mass of adsorbent (mg/g)
C_o= initial solution concentration (mg/L)
C_e= final/equilibrium solution concentration (mg/L)
V = solution volume (L)
W= mass of adsorbent used (g)
%R= percentage removal (%)

Adsorption kinetics describes the process by which an analyte is adsorbed onto an adsorbent as a function of time. The pseudo-first order (PFO) and pseudo-second order (PSO) kinetic models were employed to identify the adsorption mechanism [14]. The pseudo-first order model can be expressed mathematically as follows:

$$In\ (qe\ -\ qt) = In\ (qe)\ -\ k1t \quad (3)$$

Information:
q_e = equilibrium adsorption capacity (mg/g)
q_t = adsorption capacity at time *t* (mg/g)
k_1 = adsorption rate constant (min^{-1})

The pseudo-second order (PSO) model can be expressed mathematically as follows:

$$\frac{1}{qe} = \frac{1}{K2q\hat{}2} + \frac{1}{qe}\ t \quad (4)$$

Information:
k_2= adsorption rate constant (g/mg.min)
q_e= equilibrium adsorption capacity (mg/g)

An isotherm describes the adsorption process at a constant temperature. The Langmuir and Freundlich models [16] are commonly used to describe adsorption equilibrium. The Langmuir isotherm model assumes that adsorbate molecules bind to a homogeneous adsorbent surface through monolayer adsorption, with no interactions between adsorbed molecules or ions [15].

$$\frac{Ce}{qe} = \frac{1}{Kl \times qmax} + \frac{Ce}{qmax} \quad (5)$$

Information:
Linear equation y = ax + b
Slope (a) = $1/q_{max}$
Intercept (b) = $1 / (K_L . q_{max})$
X-axis = C_e
Y-axis= C_e/q_e
q_{max}= Maximum adsorption capacity (mg/g)
K_L = Langmuir adsorption constant (L/mg)

The Freundlich isotherm model assumes that adsorption occurs on a heterogeneous surface.

$$In\ (qe) = In\ (Kf) + \frac{1}{n}\ In\ (Ce) \quad (6)$$

Information:
Linear equation y = ax + b
Slope (a) = 1/n
Intercept (b) = ln (Kf)
X-axis = ln (C_e)
Y-axis = ln (q_e)
K_f = Freundlich adsorption constant
n = Adsorption intensity parameter

The existing literature on activated carbon specifically derived from oil palm fronds (OPF) remains limited. Therefore, this study investigates the adsorption isotherms and kinetics of activated carbon derived from OPF, prepared through chemical activation using 30% phosphoric acid (H_3PO_4), followed by physical activation at 500 °C for 1.5 h.

This study aims to evaluate the effectiveness of OPF-derived activated carbon prepared using a combined chemical and physical activation process. The samples were designed to simulate actual wastewater conditions containing multiple heavy metals, with sample modification using a multi-element standard [4]. This approach also provides information on metal selectivity, thereby enhancing the interpretation of the adsorption performance of OPF-derived activated carbon. Metal concentrations were determined using ICP-OES 5800 VDV at a relatively low concentration of 10 mg/L, as the instrument provides optimal analytical performance within this concentration range [17].

2. METHOD

A systematic experimental approach was employed to investigate the simultaneous adsorption of multiple elements using activated carbon prepared from oil palm fronds. The study began with the preparation and characterization of the adsorbent, followed by the preparation of aqueous solutions containing the target elements at predetermined concentrations. Batch adsorption experiments were then conducted to examine the effects of contact time and initial concentration on the adsorption process. Kinetic experiments were performed by monitoring changes in the concentration of each element at different contact times, while equilibrium experiments were carried out using a range of initial concentrations to determine the adsorption capacity of the activated carbon. The concentrations of the target elements before and after adsorption were measured using an appropriate analytical instrument.

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2.1 Activated Carbon Preparation

The oil palm frond (OPF) raw material was cleaned, and the outer layer was removed before being cut into approximately 1 × 1 cm pieces and air-dried for 3 days. The dried OPF was then soaked in 30% phosphoric acid (H_3PO_4) at a solid-to-liquid ratio of 1:5 (w/v) for 24 h [18]. The OPF was carbonized at 250 °C for 2 h, followed by physical activation at 500 °C for 1.5 h [11-14]. The resulting adsorbent was washed with de-mineralized water until a neutral pH was achieved and then dried at 105 °C for 2 h. The dried adsorbent was ground and sieved to obtain a particle size of 100 meshes to ensure a uniform specific surface area [12].

2.2 Multi element Solution Preparation

A 50 mg/L working solution was prepared by diluting Merck IV Certified Reference Material (CRM) at 1000 mg/L, containing 23 elements. The solution pH was adjusted to 5.5 using NaOH or 0.1 M nitric acid (HNO_3) [19-20]. pH adjustment was performed in a larger-volume solution prior to final dilution to minimize dilution errors and maintain sample matrix consistency.

2.3 Batch Adsorption

For the kinetic study, 0.05 g of adsorbent was added to 25 mL of a 10 mg/L multi element solution. The mixture was stirred at 120 rpm with contact times of 1, 5, 10, 30, 60, 90, 120, and 180 min. For the isotherm study, the initial metal concentrations were varied at 2, 4, 6, and 8 mg/L in 25 mL of solution using 0.01 g of adsorbent, with the contact time set according to the optimum contact time obtained from the kinetic study.

2.4 Sample Analysis Using ICP-OES

Following the adsorption process, the solutions were filtered through of 0.45µm filter paper and preserved by adding concentrated nitric acid until the pH was below 2. A calibration curve was prepared using mixed standard solutions and a blank, with standard concentrations of 1, 2, 5, and 10 mg/L. The residual metal concentrations (C_e) in the filtrates were simultaneously determined using ICP-OES 5800 VDV [21]. The adsorption capacity (q_e) was calculated based on the mass balance equation, and the experimental data were evaluated using the pseudo-first order and pseudo-second order kinetic models, as well as the Langmuir and Freundlich isotherm models.

3. RESULTS AND DISCUSSION

Adsorption is a series of interactions between the surface of a solid material (adsorbent) and a contaminant (adsorbate), occurring in either the liquid or gas phase [12]. The equilibrium relationship between the concentration of the adsorbate in the liquid phase and its concentration on the adsorbent particles at a given temperature represents the adsorption capacity of activated carbon [13].

3.1 Adsorption Kinetics

Adsorption kinetics describes the process by which an analyte is adsorbed onto an adsorbent as a function of time. The pseudo-first order and pseudo-second order models were employed to characterize the adsorption process [14]. Following the batch adsorption experiments, the filtrates were analyzed using ICP-OES 5800 VDV in accordance with SNI 6989-82:2018. The metal analysis was supported by satisfactory quality control (QC), with an accuracy of 99.14% and a precision of 1%, meeting the acceptance criteria for analytical quality specified in SNI 6989-82:2018 [21].

Table 1: Adsorption Kinetic Analysis Results for Pb(II)

Sample ID	Time (t)	Mass (g)	C_0 (mg/L)	Ce (mg/L)	C_0 - Ce (mg/L)	q_t (mg/g)	In(qe - qt)	t/qt	%Removal
K-1	1	0.05	9.9453	4.0098	5.9355	2.9677	-0.4026	0.3370	59.68
K-2	5	0.05	9.9453	2.9157	7.0296	3.5148	0.0527	1.4226	70.68
K-3	10	0.05	9.9453	2.2432	7.7021	3.8510	0.4904	2.5967	77.44
K-4	30	0.05	9.9453	1.5925	8.3528	4.1764	1.2481	7.1833	83.99
K-5	60	0.05	9.9453	1.3873	8.5580	4.2790	1.6904	14.0220	86.05
K-6	90	0.05	9.9453	1.2831	8.6622	4.3311	2.0223	20.7801	87.10
K-7	120	0.05	9.9453	1.2289	8.7164	4.3582	2.2514	27.5345	87.64
K-8	180	0.05	9.9453	1.0184	8.9269	4.4634	-	40.3278	89.76

Table 2: Adsorption Kinetic Analysis Results for Cu(II)

Sample ID	Time (t)	Mass (g)	C0 (mg/L)	Ce (mg/L)	C0 - Ce (mg/L)	qt(mg/g)	In (qe - qt)	t/qt	%Removal
K-1	1	0.05	10.2725	5.4816	4.7909	2.3955	-0.8163	0.4175	46.64
K-2	5	0.05	10.2725	4.2092	6.0633	3.0317	-0.4861	1.6493	59.02
K-3	10	0.05	10.2725	3.1698	7.1027	3.5514	-0.1009	2.8158	69.14
K-4	30	0.05	10.2725	2.1190	8.1535	4.0768	0.5433	7.3588	79.37
K-5	60	0.05	10.2725	1.6154	8.6571	4.3286	1.1117	13.8615	84.27
K-6	90	0.05	10.2725	1.3282	8.9443	4.4722	1.6852	20.1245	87.07
K-7	120	0.05	10.2725	1.2836	8.9889	4.4945	1.8134	26.6996	87.50
K-8	180	0.05	10.2725	0.9574	9.3151	4.6576	-	38.6469	90.68

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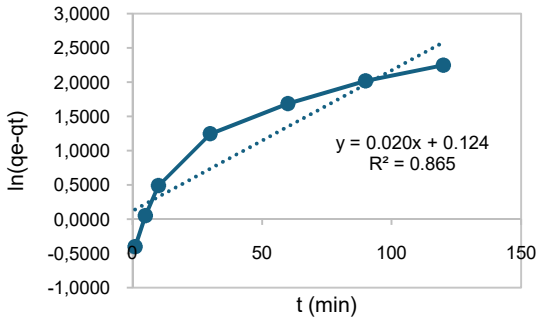
From Tables 1 and 2, it can be observed that contact time significantly affects the adsorption of Pb(II) and Cu(II), as demonstrated by the removal efficiencies at 180 min, which reached 89.76% and 90.68%, respectively demonstrated that increasing the adsorption contact time positively affects the removal efficiency of heavy metals, particularly Pb(II) and Cu(II) [14]. The pseudo-first order (PFO) model was used to determine the adsorption kinetics of the activated carbon [14]. To obtain the linear equation, a plot was constructed with contact time (t) on the x-axis and $\ln(q_e - q_t)$ on the y-axis. Similarly, the pseudo-second order (PSO) model was evaluated by plotting contact time (t) on the x-axis against t/q_t on the y-axis. Here, q_e represents the adsorption capacity at equilibrium or at an infinite contact time, q_t represents the adsorption capacity at a given contact time t, and k_1 represents the PFO rate constant [14]. Figures 1 and 2 present the linear equations obtained from the respective adsorption kinetic models. The calculated parameters of the pseudo-first order (PFO) and pseudo-second order (PSO) kinetic models are presented in Table 3.

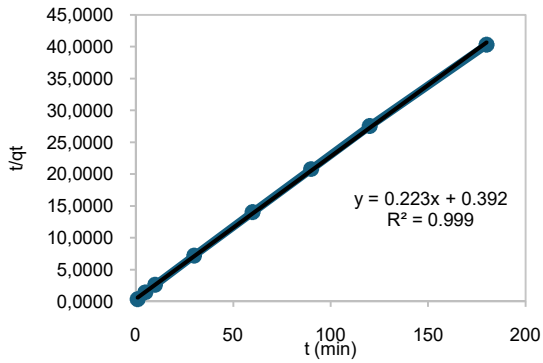
Comparison of the results indicates that both Pb(II) and Cu(II) in the pH 5.5conditioned multi element CRM sample tend to follow the pseudo-second order kinetic model. This is supported by the coefficients of determination (R^2), which were close to 1 for both Pb(II) and Cu(II), with values of 0.9997 and 0.9993, respectively. The K_2 value is directly related to the decrease in adsorbate concentration [13], explaining the rapid adsorption observed during the initial stage, followed by a gradual decrease in the adsorption rate until equilibrium is reached [13].

Table 3: Adsorption kinetic model parameters

Pseudo-First Order Pb(II)		Pseudo - First Order Cu(II)	
$q_{e,cal}$	1.0860mg/g	$q_{e.cal}$	1.8292mg/g
qe,mod	4.4634mg/g	qe.mod	4.6576mg/g
k_1	0.0329min^{-1}	k_1	0.0309min^{-1}
R^2	0.8826	R^2	0.931796081
a	-0.0825	a	-0.6039
b	0.0329	b	0.0309
r	0.9394	r	0.9653
Pseudo- Second Order Pb(II)		**Pseudo- Second Order Cu(II)**	
$q_{e,cal}$	4.4660mg/g	$q_{e.cal}$	4.6838mg/g
qe,mod	4.4634mg/g	qe.mod	4.6576mg/g
k_2	0.5702g/mg.min	k_2	0.3009g/mg.min
R^2	0.9997	R^2	0.9993
a	0.3927	a	0.7096
b	0.2239	b	0.2135
r	0.9999	r	0.9997

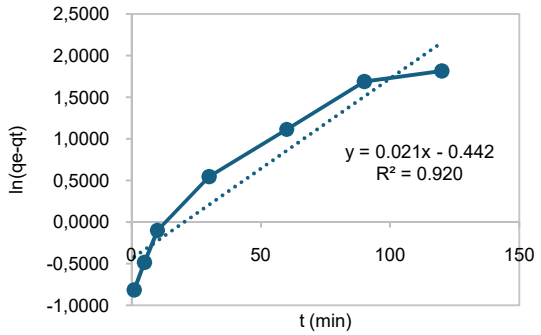


(a)

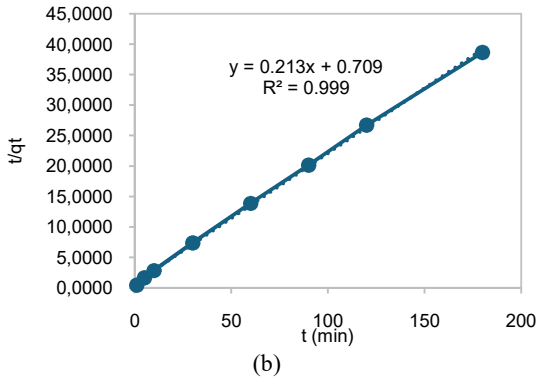


(b)

Figure 1: Kinetic Models for Pb(II): (a) Pseudo-first order and (b) Pseudo-second order



(a)



(b)

Figure 2: Kinetic models for Cu(II): (a) Pseudo-first order and (b) Pseudo-second order

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The adsorption efficiency of Pb(II) and Cu(II) by the activated carbon can be observed in Tables 1 and 2. The results show that the adsorption rate for both metals began to slow after 90 min of contact time. However, this time could not yet be considered the optimum contact time because equilibrium had not been reached, as indicated by the continued increase in q_t with increasing contact time. Therefore, the optimum contact time for the kinetic study was determined to be 180 min. This optimum contact time was subsequently used as the basis for determining the adsorption capacity using adsorption isotherm models.

3.2 Adsorption Isotherm

An adsorption isotherm describes the adsorption process occurring at a constant temperature. In this study, the Langmuir and Freundlich isotherm models were employed to characterize the adsorption behavior. Understanding adsorption isotherms is essential for evaluating the adsorption mechanisms of Pb(II) and Cu(II), thereby supporting the efficient design of adsorption systems.

The Langmuir isotherm model assumes that adsorbate molecules bind to a homogeneous adsorbent surface through monolayer adsorption, without interactions between adsorbed molecules or ions [15]. In contrast, the Freundlich isotherm model assumes that adsorption occurs on a heterogeneous surface. The adsorption isotherm experiments were conducted using the batch method, and the resulting filtrates were analyzed in accordance with SNI 6989-82:2018 using an ICP-OES 5800 VDV instrument. The metal analysis was supported by satisfactory quality control (QC), with an accuracy of 98.94% and a precision of 0.04%, meeting the analytical quality acceptance criteria specified in SNI 6989-82:2018 [21].

As shown in Tables 4 and 5, a decrease in q_e was observed compared with the previous kinetic experiments. This decrease can be attributed to the reduction in the activated carbon dosage to 0.01 g. The lower adsorbent dosage was intended to prevent complete (100%) adsorption during the isotherm analysis at low multi element concentrations, which could interfere with the evaluation of the adsorption isotherm.

Figure 3 and 4 show that the linear equations obtained from the respective isotherm models for both metals were better described by the Langmuir model. This finding is supported by the coefficients of determination (R^2), which were close to 1 for Pb(II) and Cu(II), with values of 0.9639 and 0.9953, respectively these results indicate that the adsorption process occurs on a homogeneous surface of the activated carbon through monolayer adsorption [22]. In this mechanism, metal ions are adsorbed onto specific active sites on the carbon surface until saturation is reached, thereby limiting the adsorption of other competing metal ions present in the multi element sample.

Table 4: Adsorption isotherm analysis results for Pb(II)

Sample ID	C_0 (mg/L)	Mass(g)	Volume(L)	Ce (mg/L)	qe (mg/L)	R_L
I-1	2	0.0100	0.0250	1.2764	1.8090	0.34
I-2	4	0.0100	0.0250	3.1877	2.0308	0.21
I-3	6	0.0100	0.0250	5.1411	2.1473	0.15
I-4	8	0.0100	0.0250	6.9594	2.6015	0.11

Table 5: Adsorption isotherm analysis results for Cu(II)

Sample ID	C_0 (mg/L)	Mass (g)	Volume(L)	Ce (mg/L)	qe (mg/L)	R_L
I-1	2	0.0100	0.0250	1.2342	1.9145	0.13
I-2	4	0.0100	0.0250	3.0494	2.3765	0.08
I-3	6	0.0100	0.0250	5.0894	2.2765	0.05
I-4	8	0.0100	0.0250	7.0192	2.4520	0.04

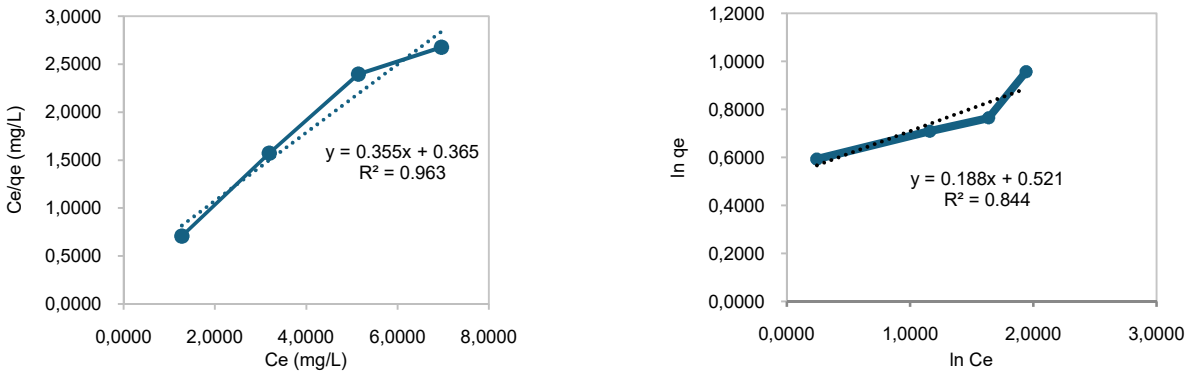

Figure 3: Isotherm models for Pb(II): (a) Langmuir and (b) Freundlich

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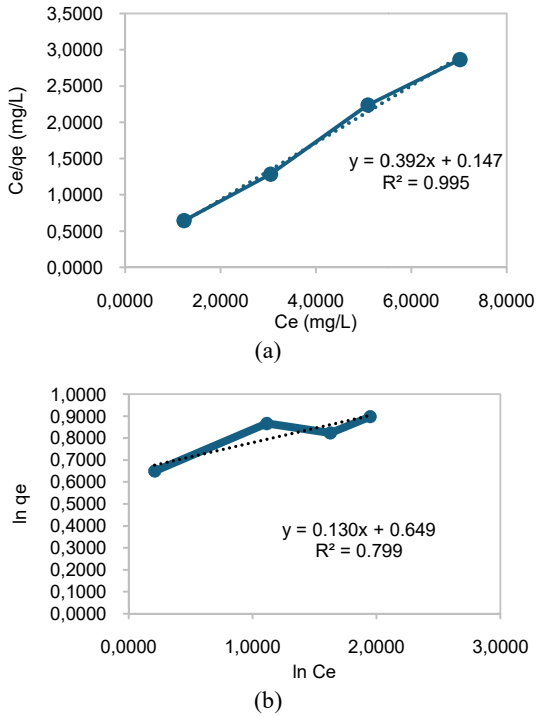

Figure 4: Isotherm models for Cu(II): (a) Langmuir and (b) Freundlich

The calculated Langmuir constants (K^L) for Pb(II) and Cu(II) were 0.9734 and 2.6555 L/mg, respectively. The corresponding separation factors (R^L) were 0.11 and 0.04, both within the range of $0 < R^L < 1$. These results indicate that the adsorption process is favorable, further supporting the applicability of the Langmuir model. Therefore, the adsorption capacity obtained from the Langmuir equation can serve as a reference for further studies [23].

However, the kinetic and isotherm results should be interpreted carefully, particularly due to the decrease in q_e observed during the isotherm analysis. This decrease may be attributed to the reduction in activated carbon dosage used in the isotherm experiments. This finding is consistent with previous research, which reported that the mass of activated carbon affects the adsorption capacity of the adsorbent toward the adsorbate [12].

Table 6: Adsorption isotherm model parameters

	Langmuir Pb(II)		Langmuir Cu(II)
q_m	2,8148mg/g	q_m	2,5474 mg/g
k_L	0,9734L/mg	k_L	2,6555L/mg
R_L	0,1142	R_L	0.0418
R^2	0,9639	R^2	0.9953
a	0,3650	a	0.1478
b	0,3553	b	0.3926
r	0,9818	r	0,9976
	Freundlich Pb(II)		Freundlich Cu(II)
K_F	1.6838mg/g	K_F	1.9140mg/g
n	5.31	n	7.68
R^2	0.8445	R^2	0.7997
a	0,5211	a	0.6492
b	0,1882	b	0.1301
r	0,9190	r	0.8942

3.3 Adsorption Selectivity

In this study, a multi element sample was used, with an initial pH below 2. The adsorption efficiency is influenced by the pH of the solution passing through the adsorption system; therefore, the sample pH was adjusted to 5.5 [19]. In addition to optimizing the adsorption of heavy metals, this adjustment was intended to simulate realistic industrial wastewater conditions. Based on the experimental results, the adsorption capacity was determined for the 23 metals contained in the multi element CRM. The adsorption selectivity of the activated carbon was then evaluated by comparing the percentage removal (%Removal) of each metal at an initial concentration (C_0) of 10 mg/L.

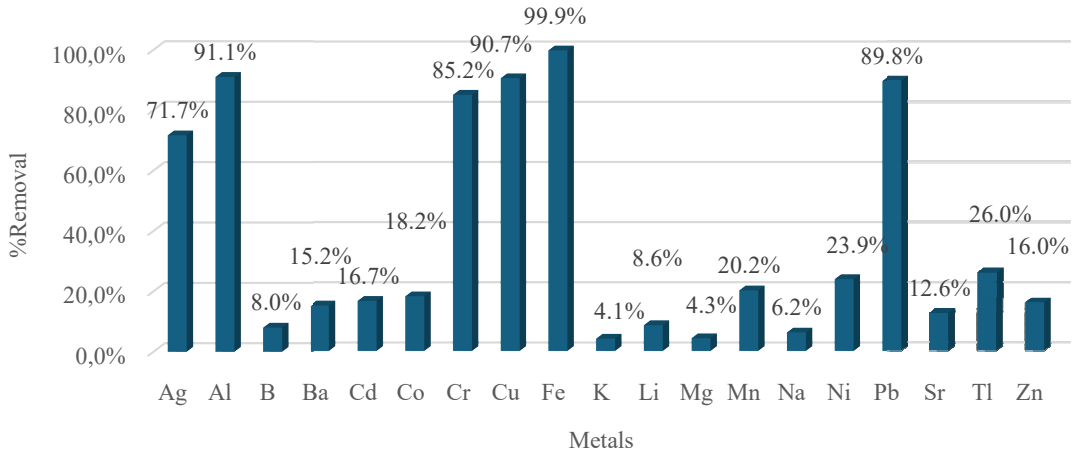

Figure 5: Adsorption selectivity

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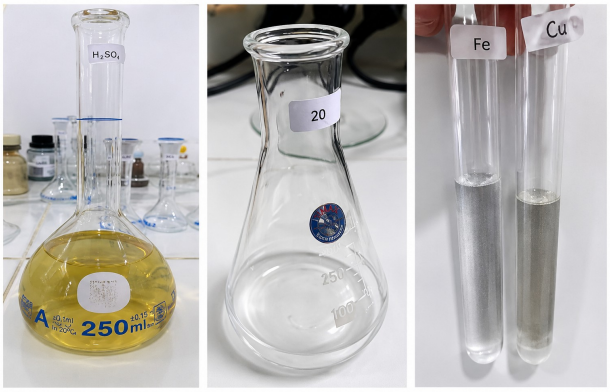
Figure 5 shows competitive adsorption among the metal ions based on the calculated removal percentages (% Removal) for each metal. OPF-derived activated carbon demonstrated high adsorption efficiency toward Fe, Al, Cu, Pb, and Cr, with removal efficiencies exceeding 80%. Moderate adsorption efficiency was observed for Ag, Tl, Ni, and Mn, with removal efficiencies ranging from 20% to 79%, while the remaining metals exhibited relatively low removal efficiencies of 4%–19%. These results indicate that OPF-derived activated carbon prepared through the applied activation process exhibits strong adsorption performance in simulated industrial wastewater containing multiple heavy metals, particularly for Pb(II) and Cu(II).



(a) (b) (c)

Figure 6: CRM solution: (a) Before adsorption, (b) After adsorption, and (c) C_e and C_0

In this study the multi element sample was adjusted to pH 5.5 to optimize the adsorption process and simulate realistic industrial wastewater conditions. However, this pH adjustment may also induce reactions involving some of the metals present in the multi element solution. One notable example is Fe, which exhibited the highest adsorption efficiency. However, analysis of the initial sample (C_0) showed an Fe concentration of only 6 mg/L. This may have occurred because pH adjustment using NaOH promoted oxidation reactions, resulting in the formation of metal oxide precipitates. This was supported by the observed color change of the multi element solution to yellow after reaching pH 5.5, as shown in Figure 6. Consequently, the maximum adsorption capacity for Fe could not be accurately determined because the Fe concentration was depleted before adsorption equilibrium was reached.

4. CONCLUSION

Based on the results of this study, activated carbon derived from oil palm fronds (OPF) and activated with 30% H_3PO_4 exhibited adsorption kinetics that followed the pseudo-second order model, with an optimum contact time of 180 min, achieving Pb(II) and Cu(II) removal efficiencies of 89.76% and 90.68%, respectively. The corresponding adsorption rate constants for Pb(II) and Cu(II) were 0.5702 and 0.3009 g/mg.min, respectively. The adsorption isotherms for the metals in the Merck VI multi element CRM were best described by the Langmuir model, with adsorption capacities for Pb(II) and Cu(II) of 0.9734 and 2.6555 L/mg, respectively. The adsorption process was favorable, as indicated by R_L values of 0.11 and 0.04 for Pb(II) and Cu(II), respectively. Adsorption selectivity analysis showed that the activated carbon was highly effective in removing Fe, Al, Cu, Pb, and Cr, with removal efficiencies exceeding 80%. Future research should focus on elucidating the adsorption mechanism, evaluating the effects of solution chemistry and temperature, investigating adsorbent regeneration, and validating the performance of OPF-derived activated carbon using real wastewater and continuous-flow systems.

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