IJIS Edu : Indonesian J. Integr. Sci. Education, 8 (1) 2026

Volume 8 Issue 1 , Januari 2026
P-ISSN: 2655-2388, E-ISSN: 2655-2450

BIOCHAR FROM PALM KERNEL SHELL AND ITS APPLICATION FOR CU^{2+} SORPTION

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Abstract: Oil palm kernel shells (KS) are a byproduct of oil palm processing that often receives little attention and is treated as waste. Biochar has various applications for example as an adsorbent. This study aims to prepare and characterize biochar from KS and evaluate its effectiveness in adsorbing Cu^{2+}. The biochar (BKS) was prepared by heating KS in a furnace at 500°C for three hours. The resulting material was sieved using a 50-mesh sieve to ensure uniformity. Characterization of BKS showed that it had a surface area of 319.9 m^2 g^{-1}, a total pore volume of 0.168 cm^3 g^{-1}, and an average pore size of 1.049 nm, classifying it as microporous. Analysis for its functional groups revealed the presence of functional groups with stretching vibrations corresponding to O-H (3400 cm^{-1}), C-H (2920 cm^{-1}), C=O (1700 cm^{-1}), C=C (1432-1690 cm^{-1}), and C-O (1000-1200 cm^{-1}). SEM imaging displayed a clear porous structure with well-defined channels. Adsorption isotherm experiments demonstrated that Cu^{2+} adsorption data using BKS aligned better with the Freundlich isotherm model than with the Langmuir model. These findings indicate that BKS derived from KS is less effective for removing Cu^{2+} ions from water compared to other biochars..

Keywords: Environment, Environmental Pollution, Garbage, Waste

How to cite this article :

Candra, I., Sari, I., Abdullah, R., Elvia, R., & Handayani, D. (2025). Biochar From Palm Kernel Shell and Its Application For CU2+ Sorption. IJIS Edu : Indonesian Journal of Integrated Science Education, 8(1). doi:http://dx.doi.org/10.29300/ijisedu.v8i1.9561

1. Introduction

Palm oil is a key commodity in Indonesia's agriculture and plantation sectors, particularly in Bengkulu Province. In 2021, it produced approximately 189.87 thousand tons of palm oil (BPS, 2021). This production is accompanied by a large quantity of KS, which have received little attention and are often discarded as waste without further utilization. Many researches have been conducted to explore the potential of transforming KS into high-performance materials.

As a biomass material, KS has a high carbon content, making it a promising candidate for conversion into biochar. Biochar is a highly porous charcoal material produced by heating biomass, a process that burns away non-carbon substances such as cellulose and lignin, leaving behind pure carbon. It has a broad spectrum of applications, including as a catalyst (Yuan et al., 2023), electrode (Sangrulkar et al., 2023), and adsorbent (Ji et al., 2024); (Liu et al., 2021); (Yao et al., 2021).

The performance of biochar as an adsorbent depends largely on several parameters that influence its ability to absorb adsorbates, such as surface area and porosity. A high surface area and porosity allow biochar to adsorb larger amounts of adsorbate. Additionally, the functional groups present on biochar play a key role in its adsorption capacity. Therefore, analyzing surface area, porosity, and functional groups is crucial when using biochar as an adsorbent.

Cu^{2+} is a common pollutant found in both water and drinking water. Numerous studies have reported Cu^{2+} ion contamination in water bodies. It is also known that Cu^{2+} can have adverse effects on human health, such as causing digestive issues and enzyme disfunctionality. Sources of Cu^{2+} include pigments, plant enrichers, chemical agents, and Steel production plants. The concentration of Cu^{2+} ions has significantly increased in both local and global water environments.

This research is conducted in response to the issues mentioned above and the limited studies on the production and characterization of biochar from KS, as well as its application for removing Cu^{2+} from water.

Online ISSN 2655-2450 | Print ISSN 2655-2388

2. Method

Materials

KS was obtained from PT Agricinal Company in North Bengkulu Regency. Copper sulfate pentahydrate ($CuSO_4.5H_2O$) and hydrochloric acid (HCl) used in this study were purchased from Merck (Germany) and Sigma-Aldrih (USA) respectively.

Biochar preparation

The dried KS was heated in an oven at a rate of 10°C per minute, reaching a maximum temperature of 500°C and maintained for three hours. The resulting biochar (BKS) was then sieved using a 50-mesh sieve to ensure uniform particle size.

Biochar characterization

The sieved BKS was characterized using the Brunauer-Emmett-Teller (BET) method to determine its surface area and porosity. Functional groups were identified using FTIR, while SEM was utilized to examine the biochar's surface morphology.

Biochars application for removing Cu^{2+} ion from water

The adsorption experiment of Cu^{2+} using BKS was performed using a batch adsorption method. In this procedure, 2.5 g of biochar was introduced into each of four 60 mL polyethylene bottles, followed by the addition of 47, 46.5, 45.5, and 43.5 mL of distilled water, respectively. The pH of the biochar–distilled water mixtures in the bottles was adjusted to 5.5 using HCl 0.1M. The mixtures were then pre-equilibrated by shaking on a shaker for 24 hours.

After pre-equilibration, specific volumes (0.5, 1, 2, and 4 mL) of a 100 ppm Cu^{2+} stock solution were spiked to the bottles to obtain final Cu^{2+} concentrations of 1, 2, 4, and 8 ppm, respectively. The mixtures were then shaken for an additional 24 hours to reach equilibrium. Finally, the mixtures were filtered, and the remaining Cu^{2+} concentrations in the filtrates were measured using a UV-Visible spectrophotometer.

Data analysis

The remaining Cu^{2+} concentration in the filtrate was used to calculate the amount of Cu^{2+} adsorbed by the biochar. The adsorption behavior of Cu^{2+} onto BKS was evaluated using the Langmuir and Freundlich isotherm models. The Langmuir isotherm equation is expressed as follows:

$$\frac{1}{q_e} = \frac{1}{q_{max}} + \frac{1}{K_L q_{max} C_e}$$

When the both sides are multiplied by C_e, the following equation is obtained.

$$\frac{C_e}{q_e} = \frac{C_e}{q_{max}} + \frac{1}{K_L q_{max}}$$

Where q_e = Cu^{2+} adsorbed on the biochars (mg/g); Ce = equilibrium concentration of Cu^{2+} in the solution (mg/L); q_{max} = maximum capacity of biochars (mg/g) and K_L = Langmuir constant. In order to obtain q_{max} and K_L, plotting C_e/q_e vs C_e was performed. Whereas, for Freundlich isotherm, adsorption of Cu^{2+} onto BKS was analyzed according to the following equation.

$$\text{Log } q_e = \log K_F + 1/n \log C_e$$

with K_F and n are Freundlich constant.

3. Result and Discussion

Preparation and characterization of biochar

The biochar produced from palm kernel shell is shown in Figure 1. The biochar exhibited a durable and robust physical texture, attributed to its high carbon content from lignin, cellulose, and hemicellulose (Wang et al., 2021). Furthermore, Mansyur et al. (2022) suggested that this physical characteristic is due to its high aromatic carbon content and well-crystallized mineral structure.

a b c

Figure 1. The biochar before grinded (a); grinding process of the biochar (b); Sieved biochar (c)

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Characterization of biochar using BET methode found that its specific surface area, total pore volume and pore size were 319.9 $m^2.g^{-1}$, 0.168 cm^3 g^{-1}, and 1.049 nm, respectively. The pore size of the biochar (< 2 nm) is chatagorized as micropore (Leng et al., 2021). BET curve of the biochar is depicted in Figure 2.

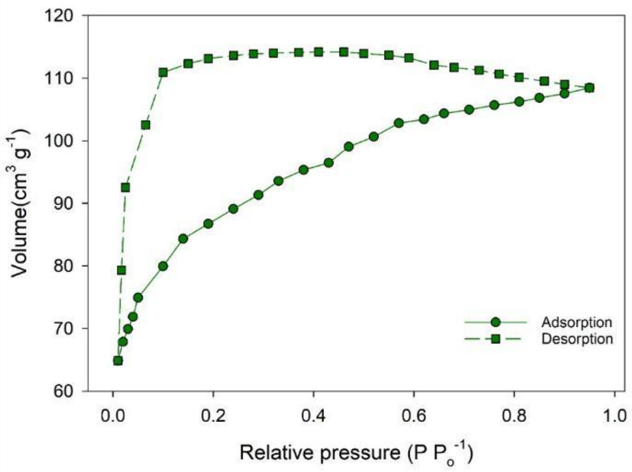

Figure 2. BET curve of biochar from oil palm kernel shell

The surface area of the biochar in this work was higher than that reported in other studies (Table 1). The temperature applied during biochar preparation plays a vital role in determining its specific surface area. It is well - known that increasing the heating temperature alters the specific surface area and porosity due to the breakdown of organic material and the formation of micropores (Yang et al., 2021).

Table 1: Specific surface area, total volume and pore size of biochar from oil palm kernel shell obtained in this study and others researches

Temp. (°C)	Duration (hour)	Heating rate (°C min^{-1})	Specific surface area (m^2 g^{-1})	Total volume (cm^3 g^{-1})	Pore size (nm)	Sources
450	1	10	36.33	0.039	28.22	Ma et al.(2017)
500	1	10	191	-	-	Lee et al.(2013)
500	1	-	208	0.21	-	Kong et al. (2019)
500	0.5	-	268	0.24	-	Kong et al. (2019)
500	1.5	-	238	0.29	-	Kong et al. (2019)
500	**3**	**10**	**319.9**	**0.168**	**1.049**	**This study**
550	1	10	98.81	0.055	23.26	Ma et al.(2017)
600	1	5	220	0.16	-	Windeatt et al. (2014)
700	3	10	90.02	0.053	2.36	Hamza et al.(2016)

note: *Heating duration at final temperature; Temp.= temperature

According to Cárdenas-Aguiar et al. (2017), during biochar production, some processes occur as the temperature increases, covering: (1) water dehydration and removal of organic volatile compounds with small molecular weight at up to 200°C, (2) the breakdown of hemicellulosic and cellulosic materials at temperature ranging from 200°C to 500°C, and (3) the disintegration of lignin and other organic materials with strong chemical bonds at temperature more than 500°C. However, excessively high temperatures can collapse the pore structure, resulting in a decrease in specific surface area. As shown in Table 1, biochar prepared at 550$_o$C, 600°C, and 700°C had a lower specific surface area compared to that prepared at 500°C in this study.

In addition to temperature, heating time is another crucial factor influencing the specific surface area of biochar. The same heating temperature with different heating durations can produce biochars with varying specific surface areas. Other parameters related to specific surface area include total pore volume and pore size. As presented

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in Table 1, while the biochar in this study exhibited a higher specific surface area compared to other studies, it had a lower total pore volume and pore size.

Total pore volume represents the cumulative volume of all pores, primarily mesopores and macropores, in the biochar. Although micropores contribute less to total pore volume, they play a dominant role in influencing the surface area of the biochar (Leng et al., 2021).

The FTIR spectrum of the biochar is presented in Figure 3. The elucidation of functional groups on the biochar through FTIR analysis revealed a broad band between 3200 and 3500 cm^{-1}, associated with the stretching vibration of O-H in alcohols and phenols, consistent with findings from other studies (e.g., Hamza et al., 2016; Pasieczna-Patkowska et al., 2025). The spectrum also exhibited a peak at 2920 cm^{-1}, corresponding to C-H stretching vibrations, primarily originating from aliphatic $–CH_2$ and alkane $-CH_3$ groups. A peak between 1650 and 1850 cm^{-1} was detected, attributed to the C=O stretching of aromatic rings. Additionally, a band at 1580 cm^{-1} was observed, which is linked to the C=O bond in -COOH groups (Guan et al., 2025). The presence of C-H deformation from alkanes or alkyl group bending was indicated by a peak at 1436 cm^{-1} (Armah et al., 2024). Furthermore, a peak at 1080 cm^{-1} identified the C-O-C stretching of ether groups.

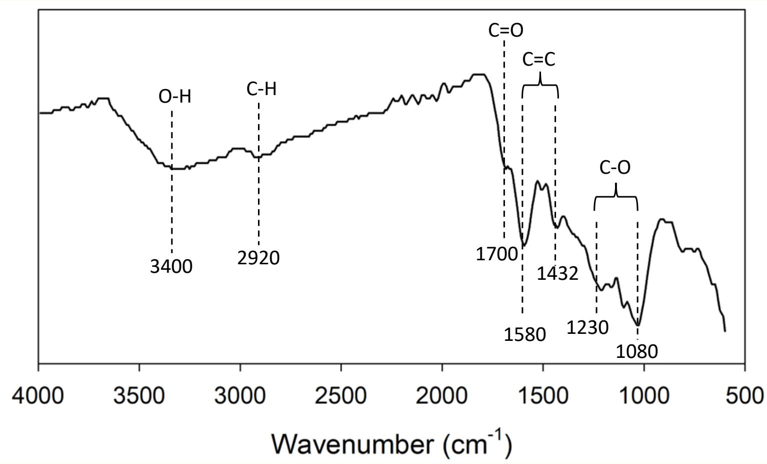

Figure 3: FTIR spectrum of biochar from oil palm kernel shell

The results of the biochar characterization using SEM are presented in Figure 4. The images reveal that the biochar surface possesses a mixed and highly complex network of pores, channels, and fibrous ridged structures, consistent with findings reported by (Saleh et al., 2025).

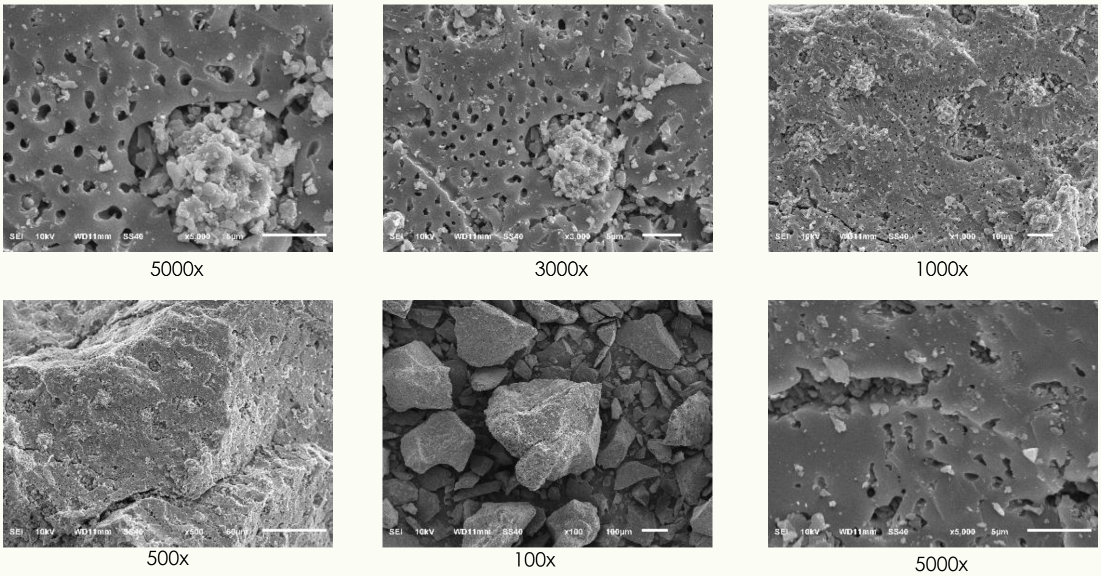

Figure 4: SEM images of the biochar with different magnification

Adsorption . This type of adsorption isotherm is characterized by an almost completely flat plateau at the saturation point of Cu^{2+} concentration in the solution (Brião et al., 2022). According to Kolesnikov et al. (2021), such an adsorption pattern is typical for microporous solids, where a strong interaction exists between the adsorbate and the adsorbent - in this case, the interaction between Cu^{2+} ions and the biochar.

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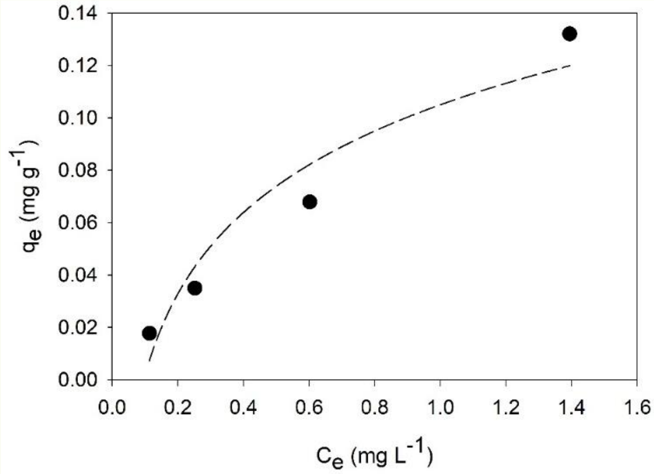

Figure 5: Adsorption isotherm of Cu^{2+} using biochar from oil palm kernel shell; C_e and q_e are concentration of Cu^{2+} in the solution and on the biochar, respectively, under equilibrium conditions.

Fitting of the adsorption data to the tested Langmuir and Freundlich isotherm models showed that both had almost the same R^2, indicating that they conformed suitably to the data. It can be concluded that the data fit well at the borderline between the Langmuir and Freundlich models, with R^2 values of 0.95 and 0.999, respectively (Figure 6).

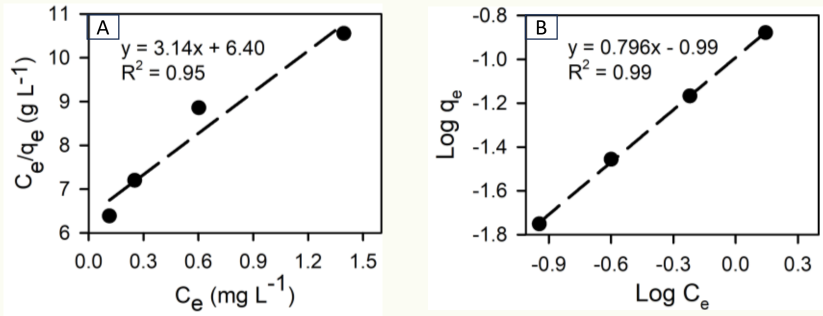

Figure 6. Data of Cu^{2+} adsorption using biochar from oil palm kernel shell fitted to Langmuir (A) and Freundlich (B) model

From the equation obtained by plotting the data to Langmuir and Freundlich Models, their parameters (q_{max}, K_L, K_F and n) were calculated. Langmuir and Freundlich parameters are presented in Table 2.

Table 2. Langmuir and Freundlich parameters for Cu^{2+} adsorption using biochar from oil palm kernel shell

Parameters	Model	
	Langmuir	Freundlich
q_{max} (mg g^{-1})	0.318	-
K_L (L.mg^{-1})	0.49	-
R^2	0.95	
K_F	-	0.1
n	-	1.25
R^2	-	0.99

Maximum adsorption capacity of Cu^{2+} (q_{max}) using the biochar in this study was smaller (0.318 mg g^{-1}) compared to adsorption of Cu^{2+} using other biochars, despite it had higher specific surface area. For example, adsorption of Cu^{2+} in aqueous solution using wheat straw biochar with specific surface area of 3.18 m^2 g^{-1}, had the highest capacity of 8.8 mg g^{-1} (Wang et al., 2022). Moreover, Kaya et al. (2020) reported maximum capacity of 14.73 mg g^{-1} for adsorption of Cu^{2+} using biochar from Hazelnut whose specific surface area was 124.3 m^2 g^{-1}. This showed that, besides specific surface area, other factors also determine maximum adsorption capacity of biochar for instance, functional groups. Pathirana et al. (2019) found that specific surface area is not the main factor, but surface functional groups are the key parameter influencing heavy metal adsorption capacity of adsorbent. Langmuir constant (K_L) was higher compared to that reported in other researches, investigating Cu^{2+} adsorption using different biochar (i.e. Wang et al., 2022). This constant represents the affinity of the adsorbate for the adsorbent.

Freundlich constant (K_F) represent adsorption capacity of adsorbent that is analogous to q_{max} in the Langmuir isotherm. Other Freundlich parameters is n, indicating adsorption intensity and favorability. This parameter can be >1, =1, or <1, indicating favorable adsorption, linear adsorption or unfavorable adsorption, respectively. When 1/n close to 1, it indicates more uniform surface. In this study, n was 1.25, indicating favorable adsorption and suggesting a more homogenous surface.

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4. Conclusion

Biochar from unused waste material of oil palm kernel shell has been successful prepared under temperature of 500°C for three hours. Characterization of the biochar showed clear pores and channel formation. The pore was classified as micropore that more contribute to the high specific surface area of the biochar. Despite having higher specific surface area, the biochar had lower maximum adsorption capacity, compared to other studies, investigating Cu^{2+} adsorption using different biochar. However, specific surface area is not the main contributor governing maximum adsorption capacity. It was reported by other study that surface functional group was the key parameter influencing maximum adsorption capacity. Further investigation is required to explain why biochar with a high specific surface area has a low maximum adsorption capacity. Moreover, modifying biochar could potentially improve its maximum adsorption capacity.

Acknowledgments

We would like to express our gratitude to Institute for Research and Community Service, University of Bengkulu throught Faculty of Education and Teacher Training for providing funding in this research. This research was conducted according to contract: 3730/UN30.7/PP/2024. We believe that this research would not have been possible without this financial support.

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