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Low-Temperature Carbonization on Biochar from Agricultural Waste for Heavy Metal Removal

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Abstract

Biochar from agricultural waste has many applications in the field of agricultural and wastewater treatment. In this study, biochar derived from exhausted kahwa coffee (EKC) was produced at low carbonization temperatures (200–400°C) for the removal of copper (II) ions (Cu2+) from aqueous solutions. The EKC biochar exhibited a removal efficiency of 92.5% under optimal conditions. The biochar was also subjected to surface characterization for further investigation of the varied capacity removal of the EKC biochar at low temperatures. BET analysis was performed on the EKC biochar to gather information on the surface area and pore size, and the structure of the formed pores was imaged using SEM. Furthermore, the elemental content and functional groups on the surface of the EKC biochar were determined by EDX and FT-IR analyses. The results showed that the surface and pore sizes of the EKC biochar had an interplay with the capacity removal of the EKC biochar during low-temperature carbonization. Meanwhile, it was also confirmed that the elemental ion content and the surface functional groups showed a stronger relation to the removal capacity of the EKC biochar at each low temperature applied.

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1. Introduction

Indonesia, an agricultural-based country, is heavily dependent on farmers who constitute the backbone of the economy (FAO, 2019). However, escalating concern regarding agricultural waste in recent years has underscored its potential to induce substantial environmental issues. With appropriate management, agricultural waste can offer significant opportunities for material recovery, value addition, resource conservation, and ecological sustainability (Viaggi 2022).

In the context of agricultural commodities, coffee ranks as Indonesia's fourth-largest foreign exchange earner, followed by palm oil, rubber, and cocoa. Remarkably, Indonesia is one of the world's leading coffee producers and exporters, with its coffee-harvested area second only to that of Brazil. Reports indicate that coffee production in 2023 reached 760.2 thousand tons (Coffee Industry in Indonesia Report - Production & Export - Analysis | Indonesia Investments, 2024; World Coffee Research | Indonesia, 2024). Consequently, coffee by-products such as shells, stalks, leaves, and husks contribute significantly to Indonesia's agricultural waste challenge. These by-products can be repurposed for diverse applications, including the production of biofertilizers, feedstock for energy generation, chemical recovery, and adsorption of chemicals, heavy metals, and dyes (Blinová et al., 2017; Mussatto et al., 2011; Torres-Valenzuela et al., 2019). Utilizing agricultural by-products to foster environmental sustainability can enhance the quality of air, water, soil, plants, animals, and energy resources. The effective management and implementation of these practices are crucial for attaining Sustainable Development Goals (SDGs).

Techniques for converting agricultural solid waste into biochar for water treatment are currently under development, supporting SDGs 2 (Zero Hunger) and 6 (Clean Water and Sanitation). The growing interest in biochar has led to an increase in the conversion of biomass into this valuable material. Biochar derived from agricultural waste is recognized as an effective, efficient, user-friendly, and eco-friendly adsorbent for wastewater treatment (Awogbemi and Kallon, 2023). It has been reported that 10.7 million tons of agricultural waste can be converted to 3.1 million tons of biochar (Putri et al., 2023).

Research on the production and utilization of biochar from agricultural waste is not new. Common conversion methods include pyrolysis, carbonization, and gasification. However, to achieve optimal biochar production, the technique must be suited to the specific type of biomass (Puari, Azora, Rusnam, Yanti, et al., 2024; Puari, Yanti, et al., 2024; Yaashikaa et al., 2020). Carbonization temperature was identified as the most critical factor influencing the carbonization of biochar from coffee byproducts. Elevated temperatures cause significant mass loss of the lignin and hemicellulose components of agricultural waste, leading to the formation of carbonaceous solid residues (Liu et al., 2018; Puari, Yanti, et al., 2024). However, higher carbonization temperatures result in increased energy consumption (Puari et al. 2022). Therefore, comprehensive research is urgently needed to explore biochar production from coffee byproducts at low temperatures for wastewater treatment.

The high-temperature method, ranging from 400 to 800°C, facilitates the synthesis of carbon nanotubes, graphite carbon materials, and activated carbon materials (Yoganandham et al., 2020). Conversely, functional carbon materials can be produced via dehydration and polymerization reactions in a low-temperature hydrothermal carbonization process at temperatures below 300°C. This study aimed to evaluate the performance of biochar for heavy metal adsorption after carbonization at temperatures below 400°C. Exhausted Kahwa Coffee (EKC), a by-product of the coffee infusion process, was used as the biomass source in this study. Further investigations into material characterization, including pore size, surface morphology, and functional groups, will be conducted using BET, SEM, and FT-IR analyses. Finally, the performance of coffee by-product biochar was analyzed and compared.

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2. Materials and Methods

2.1 Biochar Production

For biochar production, exhausted kahwa coffee (EKC) was collected from a local kahwa coffee shop in the Tanah Datar region of West Sumatra, Indonesia. The biomass was washed and dried at temperature of 150ºC for 8h prior to carbonization in a Muffle Furnace (Nabertherm B180) at various temperatures in the range 200 – 400°C at intervals of 100°C. The carbonization time and gradient were kept constant at 120 min and 5 °C/min, respectively. The detailed carbonization process followed the procedure described by Puari et al. (Puari, Azora, Rusnam, Yanti, et al., 2024). The EKC (EKC-BC) was ground and sieved into particles < 297 μm before performing biosorption performance analysis.

2.2 Yield (%), Ash Content (%) and Chemical Compositions

The yield and ash content of EKC-BC at various carbonization temperatures were quantified and expressed as percentages. The yield was calculated using Equation. (1):

$$Y\ (\%) = \frac{W}{W_o}\ x\ 100\% \quad (1)$$

where Wo is the initial weight of the EKC before carbonization and W is the final weight of the EKC in the form of biochar after carbonization.

Ash content was determined using a modified version of the biochar analysis method (Aller et al., 2017). Briefly, the ash mass was measured using an analytical balance after heating the samples at 730 °C for 10 h. The ash content was calculated using Equation (2):

$$\%\ Ash = \left(\frac{M_{ash}}{M_{OD-BC}}\right)\ x\ 100\% \quad (2)$$

where Mash is the mass in grams of the sample after heating and MOD-BC is the mass in grams of oven-dried biochar before heating.

The chemical compositions of the EKC, namely cellulose, hemicellulose, and lignin, were determined using a modified version of TAPPI. Lignin was determined using TAPPI 222 om-02, hemicellulose using TAPPI T 249, and cellulose using TAPPI T203 as previously described by Betene et al., 2020. The content determinations were defined using Equations (3), (4), and (5) for lignin, hemicellulose, and cellulose, respectively:

$$\%L = 100\ x\ \frac{m_L}{m_{res2}} \quad (3)$$

$$\%H = \ \%HC - \ \%C \quad (4)$$

$$\%C = 100\ x\frac{m_C}{m_{HC}}\ (1 - \ \%HC) \quad (5)$$

where mL is the mass of lignin extracted, mres2 is the dry mass of residue 2, %HC is the holocellulose content, %C is the cellulose content, mc is the mass of cellulose obtained, and mHC is the mass of holocellulose removed.

2.3 Performance Analysis

The performances of various EKC-BC biosorbents for heavy metals were evaluated by conducting a batch biosorption study. A copper (II) solution was prepared for the batch study of the performance of EKC-BC. Heavy metal solutions were prepared by diluting standard stock solutions of $Cu(NO_3)_2$ (1000 mg/L) with sterilized distilled water in a 100 mL flask. The standard stock solutions were of analytical grade and purchased from a local supplier of Merck in Indonesia.

The batch study was conducted by adding 1 g of each biochar to a 250 mL erlenmeyer flask containing 100 mL of the heavy metal solution with an initial concentration of 20 mg/L. The mixture was shaken by placing the flask on an orbital shaker (SK-0330 PRO Nesco Official) at 150 rpm for 2h at room temperature. Whatman 42 filter paper was used to filter all samples after the biosorption process to remove the biochar from the solution. The residual concentration of each heavy metal ion in the filtrate was measured using an Atomic Absorption Spectrophotometer (AAS) (AA-6880, Shimadzu, Japan) to determine the removal efficiency (RE) and adsorption capacity (q_t) using Equations (6) and (7), respectively.

$$Removal\ efficiency\ (\%) = \frac{(C_i - C_f)}{C_i}\ x\ 100\% \quad (6)$$

$$Adsorption\ capacity\ \left(\frac{mg}{g}\right) = \frac{(C_i - C_f)}{m}\ x\ V \quad (7)$$

where c_i, c_f, m, and v are the initial and final concentrations (mg/L) of the heavy metal ions, mass of biochar, and volume of the heavy metal solution during biosorption, respectively.

2.4 Material Characterization

The EKC biochar dried at various carbonization temperatures was characterized in terms of the quality and quantity of pores on the surface. The sample preparation was varied according to the characterization instruments. The quality of the pores was analyzed by scanning electron microscopy (SEM) at 20 kV (JEOL JSM-65110LA). The SEM instrument was equipped with an energy-dispersive X-ray spectroscope (EDX) (JEOL JSM-65110LA detector) and was used to evaluate the presence of elemental ions on the material surface. The surface area and pore size of the biochar were examined by Brunauer Emmett-Teller (BET) analysis using a Quantachrome QuadraWin ©2000-16, Quantachrome Instruments).

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2.5 Statistical Analysis

Data were collected in triplicate for removal efficiency (RE) and adsorption capacity (qt), and the means are presented. All data were analyzed using the SPSS Statistics software (version 22.0; one-way analysis of variance). The confidence level for this test was set at 99%, and statistical significance was set at $P < 0.05$.

3. Results and Discussion

3.1 Temperature effect on yield and ash content

Several studies on various biomass precursors have demonstrated that the applied carbonization temperature significantly influences the biochar yield. In this study, the yield and ash content of EKC biochar were analyzed to assess the effects of low carbonization temperature. The results presented in Figure 1 indicate contrasting trends between the yield and ash content. Specifically, while the yield of EKC biochar decreased with increasing carbonization temperature, the ash content increased.

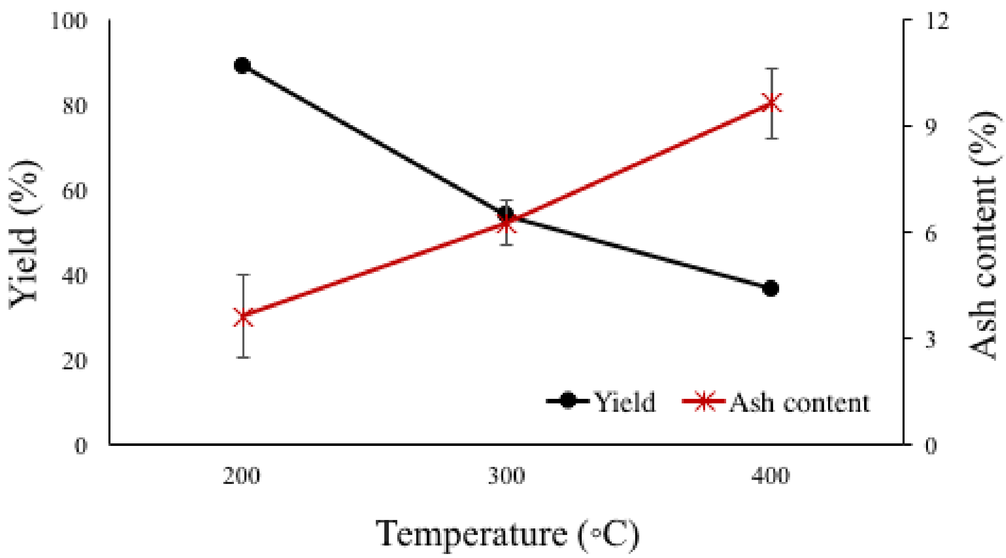

Figure 1. Yield and ash content of EKC biochar at different low temperatures (200 – 300°C).

The yield of EKC biochar was 89.4% at a carbonization temperature of 200°C. However, when the temperature was increased to 100°C, the yield decreased significantly by 35%, resulting in a yield of 54% at 300°C. Similar trends have been reported in previous studies (Nwajiaku et al., 2018; Singh Karam et al., 2022), where various biomass types underwent carbonization at temperatures below 300°C, as presented in Table 1. The Table shows that biochar produced at 200°C from two different precursors yielded over 90% yield with different biomass characteristics. However, increasing the temperature to 300°C substantially reduced the yield by ~ 30%. The decrease in the yield continued as the temperature increased to 400°C, although the reduction became less pronounced above 400°C,

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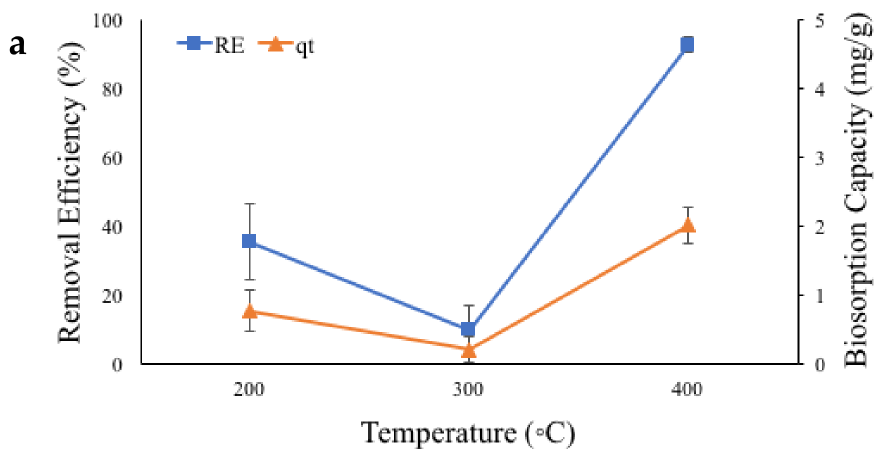
with a decline of less than 10% (Puari et al., 2024). The slower yield reduction at temperatures above 400°C can be attributed to the gradual decomposition of high-boiling, less volatile compounds. During this process, the release of volatiles leads to progressive formation of aromatic and heteroaromatic compounds (Mašek et al. 2013; Yaashikaa et al. 2020).

Table 1. Comparison of yield and the relation with the characteristic of biomass at 200°C.

Sample	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Yield (%) at 200°C
Exhausted Kahwa Coffee (EKC) (This study)	26.83	34.95	25.42	89.4
Bamboo (Zhang et al., 2017)	20.13	47.29	23.21	95.9
Exhausted Coffee Husk (ECH) (Rusnam et al., 2024)	13.57	41.13	28.13	72.3

3.2 Performance analysis (RE and q_t)

This study evaluated the performance of EKC biochar produced through low-temperature carbonization for the removal of Cu(II) ions. Biochar samples carbonized at various low temperatures underwent biosorption for 120 min. During this process, 1 g of biochar was added to a metal ion solution with an initial Cu(II) concentration of 20 mg/L. The removal efficiency (RE) and biosorption capacity (qt) of each EKC biochar were compared, as shown in Figure 2a. The results indicate that the biochar samples exhibited varying RE and qt values.



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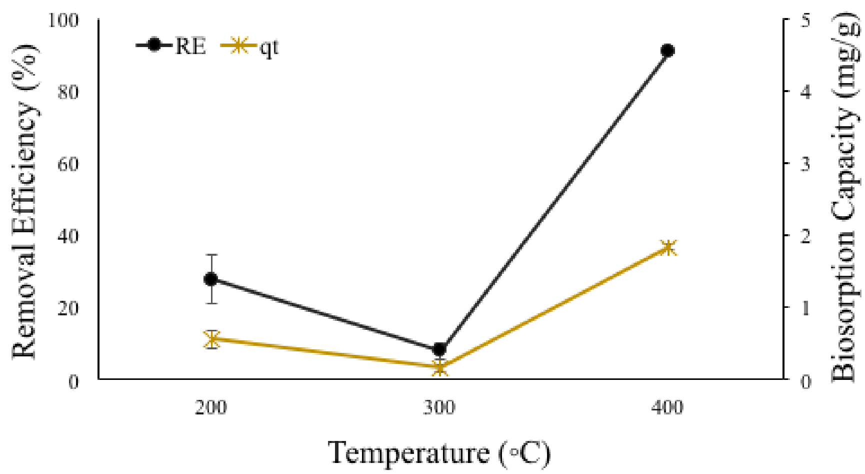

Figure 2. The performance of a) EKC biochar in terms of RE and qt for Cu (II) removal in this study and b)ECH biochar for Fe (II) removal reported by Rusnam et al. (2024).

In this study, Cu^{2+} cations were effectively removed by biochar produced at temperatures of ≤ 400°C. Theoretically, higher carbonization temperatures tend to increase the availability of pores in biochar, thereby enhancing its removal efficiency. Interestingly, Figure 2a shows that the biochar produced at the lowest temperature of 200°C achieved higher RE and q_t values than the biochar produced at slightly higher temperatures. However, both RE and q_t increased significantly when the carbonization temperature increased from 300 to 400°C, with the biochar produced at 400°C exhibiting the highest performance, with a q_t of 2.18 mg/g. A similar trend was observed in a study by Rusnam et al. in 2024 (figure1. 2b), who investigated biochar derived from exhausted coffee husks (ECH) for Fe removal. The ECH biochar produced within a comparable temperature range demonstrated a fluctuating trend in performance with increasing carbonization temperatures. Similarly, Gao et al., 2015 reported a fluctuating trend in biochar derived from agricultural residues for ammonium removal, in which biochar produced at lower temperatures exhibited higher cation adsorption.

The one-way ANOVA test indicated a significant relationship ($p < 0.01$) between the carbonization temperature and biosorption capacity (q_t) of EKC-BC for Cu^{2+} removal from the solution. These results suggest that the low-temperature carbonization process not only influences the biosorption capability of EKC biochar but also highlights that higher temperatures do not necessarily enhance the removal of ions from the solution. Previous studies by Uchimiya et al., 2011 and Gao et al., 2015 have reported that low-temperature biochar tends to possess a higher concentration of surface oxygen-containing functional groups, which can effectively interact with the cations in aqueous solutions. However, several additional factors significantly affect the cation removal efficiency of biochar. These include pore availability, pore size, surface functional groups, and cation content within the biochar, all of

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which are influenced by the temperature applied during biochar production Liu et al., 2018; J. Sun et al., 2017.

3.3 Biochar characterization (SEM-EDX, FT-IR and BET)

The EKC biochar was characterized to evaluate its potential for removing the targeted pollutant and to predict its removal performance based on its structural and elemental properties. In this study, biochar characterization was performed using several techniques: BET analysis for surface area and porosity, SEM-EDX for surface morphology and elemental composition, and FT-IR for identifying surface functional groups.

3.3.1 BET Pore Structure Analysis

Biochar with increased surface area and high porosity typically exhibits enhanced sorption properties. The porous surface of biochar forms during the carbonization process, and temperature plays a critical role in its development. The surface area and porosity of the EKC produced at the three different carbonization temperatures were analyzed using BET, and the results are presented in Table 2.

Table 2. Surface area and porosity analyses of the EKC biochar at various temperatures and other biomasses at different temperatures.

Temperature (°C)	Surface area (m^2/g)	Pore size (nm)
200	1.31	89.72
300	1.85	25.63
400	2.27	61.86
EKC 500 (Yanti et al., 2025)	17.81	1.98
BDB 300 (Xue et al., 2019)	0.4121	-
FPB 300 (Xue et al., 2019)	1.6566	-

BET analysis (Table 2) revealed that varying carbonization temperatures resulted in biochars with different surface areas. In addition, the BET results from this study showed a promising surface area, as the surface area at 300°C in this study was higher than that in a previous study (Xue et al., 2019) with different biomasses at the same temperature. A positive trend was observed, where higher temperatures during carbonization produced biochar with larger surface areas, reaching a maximum of 2.274 m^2/g at 400°C. Yaashikaa et al., 2020 emphasized that surface area is a key factor in determining the sorption capacity of biochar. This finding aligns with the ANOVA in this study,

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which showed a significant relationship ($p < 0.05$) between the surface area of the EKC biochar and its biosorption capacity (q_t). Specifically, the EKC biochar produced at 300°C, with a surface area of 1.85 m^2/g, demonstrated higher removal performance than the biochar produced at 200°C, with a surface area of 1.31 m^2/g, in terms of RE and q_t. Despite this, a fluctuating trend was observed between the surface area and removal capacity (Figure 3a).

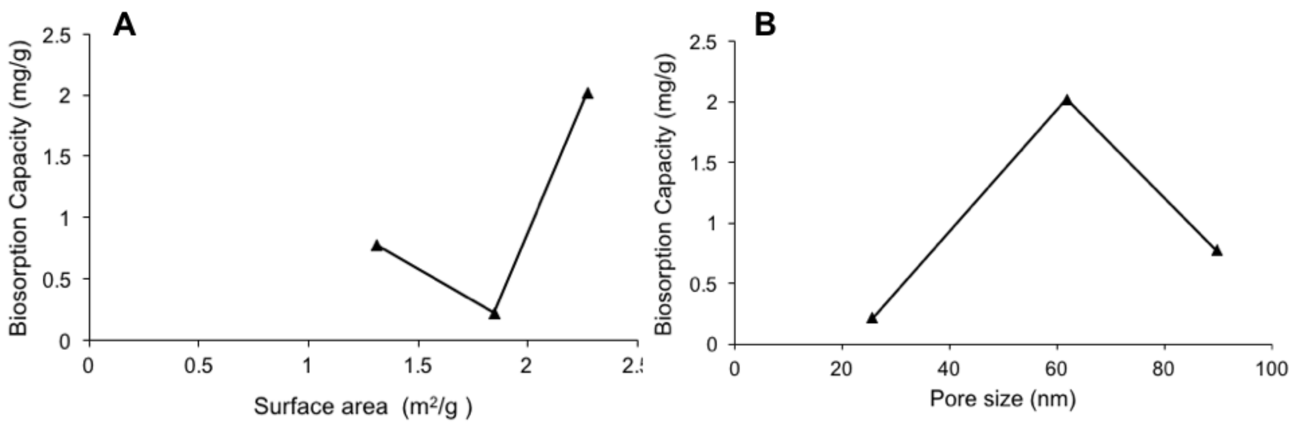

Figure 3. Relations of (a) surface area and (b) pore size with biosorption capacity.

Further examination of the pore sizes of the EKC biochar (Table 2) revealed that the varied carbonization temperatures produced different pore sizes, which also affected the biosorption capacity (Figure 3b). This observation was supported by statistical analysis, which demonstrated a significant relationship between the pore size and biosorption capacity. According to the International Union of Pure and Applied Chemistry (IUPAC) classification (Donohue & Aranovich, 1998), biochar produced at 200°C and 400°C exhibits macropores (pore size > 50 nm), whereas biochar produced at 300°C displays mesopores (pore size 2–50 nm). The pore size analysis indicated that the EKC biochar produced at 300°C had the smallest pore size (25.63 nm), which corresponded to the lowest RE and q_t; however, the largest pore size at 200°C did not align with the highest RE and qt results (Figure 3b). This suggests that other factors, such as the surface area, also influence the biochar sorption capacity, as evidenced by the highest surface area observed at 400°C. These findings indicate a possible interplay between surface area and pore size in determining the removal capacity of EKC biochar in this study. Additionally, other parameters related to the surface characteristics of biochar may contribute to its performance and warrant further investigation.

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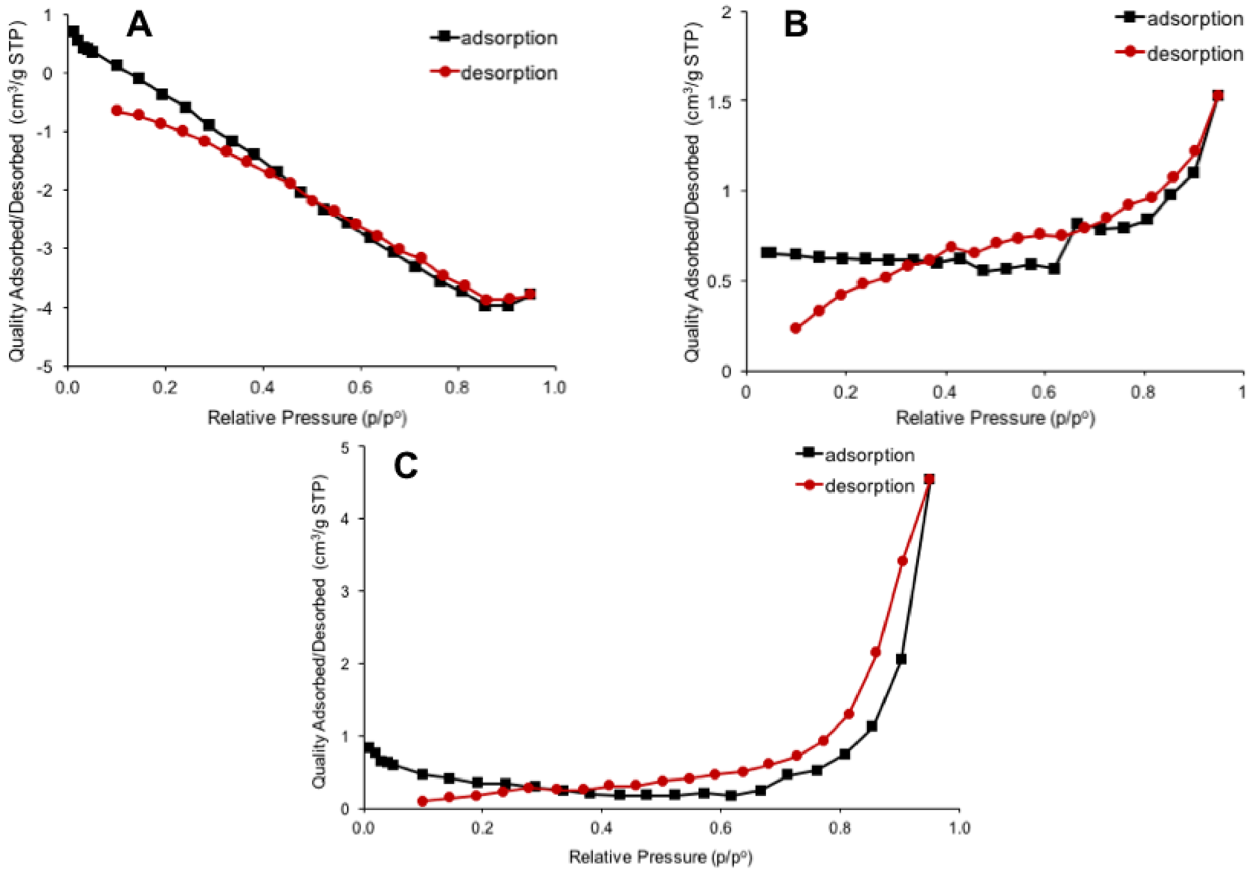

Figure 4. N_2 adsorption/desorption isotherms of the EKC biochar at (a) 200°C, (b) 300°C, and (c) 400°C.

The pore size distributions are shown in Figure 4. Interestingly, the trend of the N_2 adsorption/desorption isotherms did not resemble that of conventional increasing adsorption isotherms. If we assume that the original isotherm follows a typical behavior before differentiation, the classification by the International Union of Pure and Applied Chemistry (IUPAC) of pore size and gas sorption, the EKC biochar at a temperature of 200°C was categorized as Type II, while the other two at 300°C and 400°C were IV and III, respectively. Although there were no related results previously, the declining trend from biochar, indicating the gas adsorption/desorption performance, would be related to the accessibility of pores and their structure (Karimi & Taherzadeh, 2016), as an effect of the temperature applied during the carbonization process.

3.3.2 SEM-DEX

The surface structures of the EKC biochar were analyzed using SEM, and EDX analysis was conducted to determine the elemental composition. The SEM images are presented in Figure 5, and the elemental compositions are summarized in Table 3. The SEM images of the EKC biochar

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morphology revealed significant variations in the surface structure due to changes in carbonization temperature. Generally, an increase in the carbonization temperature is expected to enhance pore development in biochar. However, this trend was observed in this study, where the EKC biochar produced at 200°C (Figure 5a) displayed a visibly more porous structure than that produced at higher temperatures, consistent with the BET pore size analysis results. An opposing trend in the pore development with increasing temperature was also reported by Sun et al., 2020.

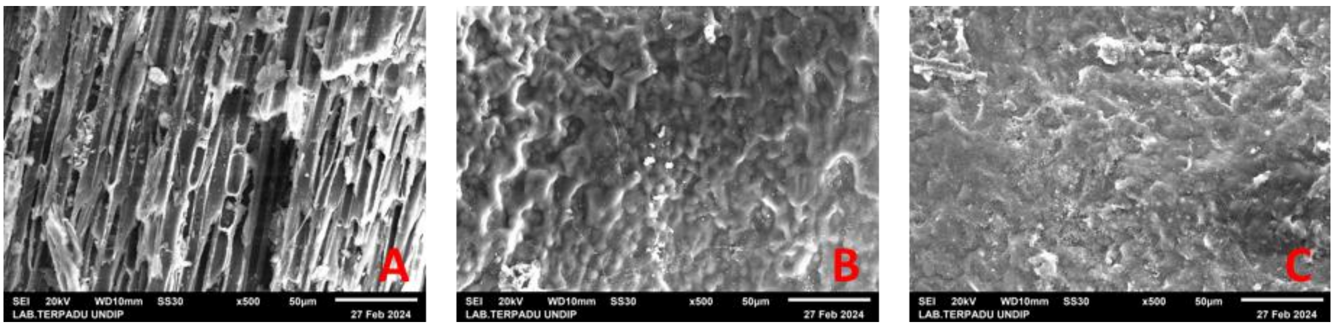

Figure 5. SEM analysis of the surface morphology of the EKC biochar at carbonization temperatures of (a) 200°C, (b) 300°C, and (c) 400°C.

It has been noted that high temperatures are generally advantageous for the formation of micropores. However, the BET analysis in this study suggests that lower carbonization temperatures most likely resulted in the production of biochar with macro-and mesopores. Additionally, Sun et al., 2020 indicated that higher temperatures may not lead to the formation of new pores and could even cause the collapse of existing pores. SEM images of the different stages of EKC biochar production, ranging from room temperature to the highest carbonization temperature of 400°C, illustrate this phenomenon. At 200°C, biochar with macrosized pores is produced. However, as the temperature increased to 300°C and then to 400°C, the existing pores began to collapse, instead of developing micropores.

EDX analysis revealed that the surface of the EKC biochar produced at different carbonization temperatures contained a range of elements, with carbon and oxygen being the major components, as shown in Table 4. Notably, the biochar produced at 400°C had the lowest carbon content and highest oxygen content. This trend indicates that increasing the carbonization temperature leads to a reduction in the carbon content and a corresponding increase in the oxygen content. In addition to carbon and oxygen, variations in the composition of other elements were observed with increasing temperature. For instance, the concentration of magnesium (Mg) increased with higher carbonization temperatures, whereas zinc (Zn) exhibited the opposite trend, with its concentration decreasing. The concentrations of other elements such as potassium (K), calcium (Ca), and copper (Cu) fluctuated as the temperature changed. These findings confirm that the elemental composition of the EKC biochar

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is influenced by the carbonization temperature used during production. In a previous study by Puari et al., 2024, ion-exchange reactions were identified as a mechanism for Cu^{2+} removal using EKC biochar. The elemental composition results suggest that the decrease in carbon content at higher temperatures corresponds to an increase in the concentration of other elements. The higher percentage of ionic elements observed at 400°C could contribute to the enhanced removal performance observed at this temperature despite not having the largest pore size.

Table 4. Elemental composition of the EKC biochar at 200, 300, and 400°C.

Element	Biochar A (200°C)	Biochar B (300°C)	Biochar C (400°C)
C	95.09	93.65	92.91
O	1.29	1.72	2.03
Mg	0.31	0.42	0.91
Si	-	-	0.08
K	0.45	0.39	0.79
Ca	0.86	1.96	1.77
Cu	0.55	0.68	0.60
Zn	1.45	1.17	0.91

3.3.3 FT-IR

To further investigate the reasons for the varied outcomes observed at different carbonization temperatures, the properties of the EKC biochar were analyzed using FTIR spectroscopy. This analysis is crucial because surface functional groups play a significant role in determining the adsorption performance of biochar for heavy metal ion removal (Puari et al., 2024). The FT-IR spectra of the EKC biochar produced at the three different low carbonization temperatures are shown in Figure 6.

Figure 6 clearly illustrates that the surface functional groups of the EKC biochar changed with increasing carbonization temperature. Overall, the spectrum of EKC 300 had the least number of peaks compared to the other two spectra. The FTIR spectra of the EKC biochar produced at 200°C showed bands at 3340, 2930, 2850, 2340, 1610, 1310, and 1020 cm^{-1}. The band at 3340 cm^{-1} is attributed to hydrogen-bonded and O–H stretching vibrations. The peaks at 2930, 2850, and 1310 cm^{-1} correspond to the C–H stretching and bending vibrations, respectively. The presence of C=C stretching vibrations characteristic of aromatic compounds was observed at 1610 $cm^{-1,}$ whereas the carboxyl group was identified by C–O stretching vibrations at 1020 cm^{-1}. At the higher carbonization temperature of 300°C, these peaks were either absent or displayed lower intensity, with only three peaks remaining at 2930, 1610, and 1310 cm^{-1} and exhibiting reduced intensity.

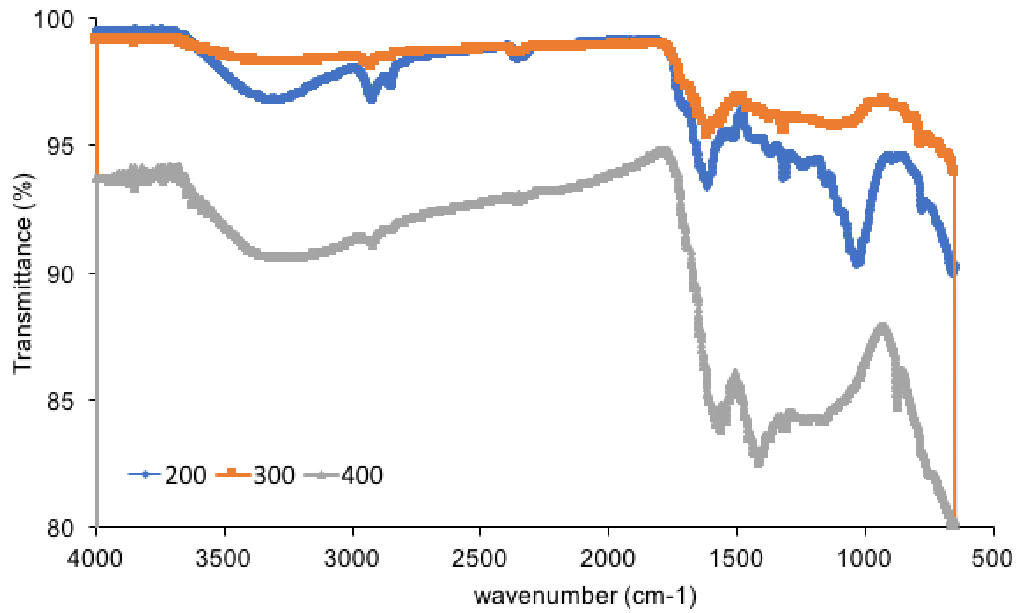

Figure 6. FT-IR spectra of the EKC biochar at various temperatures.

The FTIR spectrum at 400 °C revealed peaks corresponding to H-bonded and O–H stretching vibrations at 3300 cm^{-1} and C–O stretching vibrations at 873 cm^{-1}, which were not observed in the spectrum at 300°C. Additionally, a new peak appeared at 1540 $cm^{-1,}$ indicating C=C stretching vibrations characteristic of aromatic compounds. These findings suggest that alcohols/phenols, carboxyl groups, amides, alkanes, and aromatic compounds are present in the EKC biochar produced at temperatures of 400°C and lower. The effects of different functional groups and their relative intensities on the adsorption properties of EKC biochar were discussed in a previous study by Salim et al., 2016. This study highlighted that the carboxylic groups in biochar could play a significant role in metal adsorption, which was not observed at 300°C.

4. Conclusion

The carbonization temperature plays a significant role in the production of biochar in terms of the yield and removal performance of EKC biochar as a biosorbent. In this study, low-temperature carbonization showed potential as an alternative to biochar EKC as a biosorbent for Cu^{2+} removal via several mechanisms. The EKC that underwent carbonization at 400°C removed Cu^{2+} from the solution with various removal capacities. The trend of the varied temperature did not show a positive trend of the RE and qt, where the result was decreased when the temperature was increased from 200 °C to 300°C, and went higher up again when the temperature went up to 400°C. The highest removal

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capacity of EKC biochar was at 400°C, with q_t 2.18 mg/g, while the EKC biochar carbonized at 200°C removed 35.4% of the ions in the solution, with a removal capacity of 0.773 mg/g. The EKC biochar was characterized using BET, SEM-EDX, and FT-IR analyses to further investigate the removal trend of the EKC biochar at low temperatures. The surface area and pore size from the BET analysis indicated that both parameters play an important role in determining the removal capacity of the EKC biochar at the applied temperature. It is also noteworthy from the SEM observations that the pores were more developed at the lowest temperature of 200°C. However, the EDX results showed that the ions present in the EKC biochar had a different percentage, with the lowest being in the EKC biochar at 200°C. The results indicated that the removal was not only by the pore availability but also the other ion present with the ion exchange mechanism. The FT-IR spectra showed that the EKC biochar at 300°C had the lowest number of peaks, which represented the number of functional groups on the surface of the biochar produced. This finding led to the conclusion that the functional groups on the surface had a larger role in the removal performance of the EKC biochar that underwent carbonization at low temperatures in this study.

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