Lemon Extract as a Green Activator for Durian Peel-Derived Activated Carbon: Enhanced Copper Adsorption and Sustainable Waste Valorisation

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Abstract

The development of green, low-cost adsorbents from agricultural waste remains a critical challenge for sustainable wastewater treatment. Herein, durian peel waste was converted into porous activated carbon using lemon extract as a novel natural activator, and its efficiency for Cu^{2+} *removal was systematically evaluated. The activation process drastically reduced moisture content from 14% to 2% and ash content from 14% to 4%, while increasing iodine adsorption capacity from 824.85 to 888.30 mg* g^{-1}*, fully complying with SNI 06-3730-1995 standards. SEM analysis revealed a remarkable transformation in surface morphology, with pore diameters expanding from 9.42–12.6 µm (non-activated) to 12.1–15.8 µm after activation, indicating successful pore development. EDX confirmed Cu deposition (0.67 atom%) on the adsorbent surface post-adsorption, corroborating effective metal uptake. Remarkably, the activated carbon achieved 99.61%* Cu^{2+} *removal efficiency under optimal conditions (25% lemon extract, 15 min contact time), representing one of the highest performances reported for fruit peel-based adsorbents. Two-way ANOVA demonstrated that both activator concentration and contact time significantly influenced adsorption efficiency (*$p < 0.05$*). These findings provide compelling evidence that lemon extract serves as an efficient, eco-friendly chemical activator, and that durian peel-derived activated carbon holds exceptional promise for practical remediation of copper-contaminated water.*

Keywords: *Agricultural waste; Durian peel; Lemon extract; Natural activation; Copper adsorption; Green adsorbent*

1. INTRODUCTION

Heavy metal pollution in aquatic environments has become a growing global issue due to increasing industrial activities and urbanization. Among various heavy metals, copper (Cu) is one of the most frequently detected contaminants in water bodies, primarily derived from metal processing wastewater, electroplating, paint and pigment industries, electrical wire and cable industries, mining, and Printed Circuit Board (PCB) industries (Qi et al., 2023). Although copper is an essential trace element, accumulation of Cu ions at high concentrations is toxic to aquatic organisms and humans, potentially causing digestive disorders, kidney damage, anemia, and liver dysfunction (Prasojo & Muljani, 2024). The rising use of copper across industrial sectors has contributed to increasing Cu concentrations in aquatic environments, which may exceed the threshold of 0.02 mg/L established in Indonesian Government Regulation No. 22 of 2021(PP Nomor 22, 2021). These conditions indicate that Cu ion pollution poses a serious threat to environmental quality and public health, necessitating the development of effective, economical, and environmentally friendly treatment methods, particularly adsorption-based techniques using natural materials.

The adsorption method is defined as a process in which a substance accumulates onto the surface of an adsorbent, involving a solid phase (adsorbent) and a liquid phase (solvent) containing dissolved species (adsorbates) such as dyes or heavy metals (Raninga et al., 2023) Among various adsorbents, durian peel-based activated carbon is a promising candidate. According to data from the Central Bureau of Statistics (Badan Pusat Statistik) in 2023, durian production in Indonesia reached 1.85 million tons, representing a 17.05% increase compared to 2022 (1.58 million tons) (Suryaningih et al., 2025). Generally, only the flesh and seeds of durian fruit are utilized by the public, while the peels are discarded without optimal use. Durian peel is known to contain 50–60% cellulose, 5% lignin, and 5% starch. The high cellulose content of durian peel enables its use as a raw material for activated carbon adsorbent (Chitpreecha et al., 2026).

In the synthesis of biomass-based activated carbon, the activation stage plays a critical role in increasing surface area, pore volume, and the number of active functional groups through hydrocarbon bond cleavage and surface carbon oxidation, thereby enhancing the adsorption capacity of the material (Amin et al., 2023). Activation of activated carbon is commonly performed using acid- or base-based chemical activators, including HCl, H_2SO_4, KOH, and NaOH. Among these, acid activators are more widely employed because they are considered more effective in opening carbon micropores and improving adsorbent uptake capacity compared to base activators (Sholikhah et al., 2021). However, most previous studies have focused on synthetic chemical activators, which potentially generate chemical residues, are corrosive, and are less compatible with environmentally friendly and sustainable material concepts. Moreover, the utilization of local biomass as a source of natural activators in activated carbon synthesis remains relatively limited, especially for copper (Cu) adsorption applications (Chew et al., 2023).

An alternative that has potential for development is the use of natural acid sources from fruits rich in organic acids, particularly citric acid. Lemon fruit contains acidic compounds such as citric acid (5–8%), ascorbic acid, malic acid, and oxalic acid, which have potential to act as natural activators in pore formation and active group generation on adsorbents (Zahr et al., 2023). Several studies have reported the use of natural citric acid for heavy metal wastewater treatment. For instance, Thohir and Wijaya (2024) reported that activated carbon derived from corncob activated using natural acids from key lime (*Citrus aurantifolia*) and bilimbi (*Averrhoa bilimbi*) exhibited better adsorption capacity for hardness-causing ions (Ca^{2+} and Mg^{2+}) compared to synthetic HCl-activated carbon, as indicated by residual analyte after adsorption of only approximately 0.04 mmol (Thohir & Wijaya, 2024). Nevertheless, studies on the use of lemon extract as a natural activator in the synthesis of durian peel-based activated carbon for Cu ion adsorption are rarely reported. Therefore, the present study offers novelty through the utilization of lemon extract as an environmentally friendly natural activator for durian peel waste-based activated carbon to improve the effectiveness of copper adsorption in aquatic environments.

2. MATERIALS AND METHOD

2.1. Materials and Instruments

Durian peel waste obtained from durian sellers in the South Ring area of Cilegon City was used as the raw material for adsorbent preparation, while lemon extract was employed as a natural activator. Pro-analytical grade chemicals used included $CuSO_4 \cdot 5H_2O$, KI, I_2, $Na_2S_2O_3$, and starch (Merck, Germany), as well as distilled water and Whatman No. 41 filter paper. The instruments used included an analytical balance, an oven, a magnetic stirrer, a universal pH indicator, a 100-mesh sieve, and Pyrex glassware. Morphological characterization of the adsorbent was performed using a Scanning Electron Microscope (SEM, JEOL JSM-IT100, Japan), while Cu concentration analysis was conducted using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Shimadzu 1180, Japan).

2.2. Preparation and Carbonization of Durian Peel

Durian peel waste was obtained from fruit sellers in Cilegon City, then washed thoroughly to remove impurities attached to the surface. The sample was cut into small pieces and dried under sunlight for 3 days, followed by drying using an oven at 105°C for 1 hour to reduce the moisture content of the material (Husin & Hasibuan, 2020). The dried sample was subsequently carbonized using a furnace at 400°C for 2 hours. The carbonized product was cooled to room temperature, then ground using a mortar and sieved using a 100-mesh sieve to obtain a homogeneous particle size.

2.3. Activation of Carbon Using Lemon Extract

Lemon extract was prepared from fresh lemon fruit that had been washed and squeezed, then filtered to obtain the extract filtrate. Various concentrations of lemon extract (25, 50, 75, and 100%) were prepared by dilution with distilled water. A total of 15 g of carbonized carbon was mixed with 100 mL of lemon extract at each concentration variation, then stirred using a magnetic stirrer for 60 minutes. After the activation process, the mixture was filtered using Whatman No. 41 filter paper and washed with distilled water until a neutral pH was reached. The activated carbon was then dried in an oven at 60°C. The use of lemon extract as a natural activator was intended to assist in pore formation and opening of carbon pores, as well as to reduce impurities on the adsorbent surface through its organic acid content, especially citric acid.

2.4. Characterization of Activated Carbon

The obtained activated carbon was subsequently characterized to evaluate the quality of the produced adsorbent. Characterization included tests for yield, moisture content, ash content, and iodine adsorption capacity according to the Indonesian National Standard (SNI 06-3730-1995). Yield was calculated based on the mass ratio of the obtained activated carbon to the initial material mass before carbonization. Moisture content was determined by a gravimetric method through sample heating at 110°C until a constant mass was achieved, while ash content was determined through an ashing process at 600°C using a furnace. Iodine adsorption capacity was analyzed using an iodometric titration method to evaluate the adsorption capacity of activated carbon toward small molecules.

2.5. Adsorption Test of Cu^{2+} Ions

A 1000 ppm Cu^{2+} stock solution was prepared from $CuSO_4 \cdot 5H_2O$, then diluted to a 10 ppm working solution. Cu ion concentration measurement was performed using ICP-OES at a wavelength of 327.396 nm with a calibration curve constructed from standard solutions of 0–10 ppm. The adsorption test was conducted by mixing 0.5 g of non-activated carbon (as a control) and activated carbon into 100 mL of 10 ppm Cu^{2+} solution. The mixture was then stirred using a magnetic stirrer at contact time variations of 15, 30, and 45 minutes. After the adsorption process was completed, the solution was filtered using Whatman No. 41 filter paper, and the filtrate was analyzed using ICP-OES to determine the final concentration of Cu^{2+} ions. Adsorption efficiency was calculated based on the difference between the initial and final metal concentrations in the solution.

2.6. Morphological Characterization

The surface morphology of non-activated carbon and activated carbon before and after the adsorption process was observed using a Scanning Electron Microscope (SEM, JEOL JSM-IT100, Japan) at 1000× magnification. This characterization was performed to evaluate changes in surface structure, pore distribution, and the presence of impurities on the adsorbent following the activation and Cu^{2+} ion adsorption processes.

2.7. Data Analysis

This study employed a two-factor completely randomized design (CRD) consisting of lemon extract concentration (0, 25, 50, 75, and 100%) and adsorption time (15, 30, and 45 minutes) with two replications. The obtained data were analyzed using normality and homogeneity tests as statistical prerequisites. Subsequently, the data were analyzed using Analysis of Variance (ANOVA) to determine the effects of activator concentration variation and adsorption time on the removal efficiency of Cu^{2+} ions.

3. RESULT AND DISCUSSION

3.1. Synthesis of Activated Carbon from Durian Peel Waste

Activated carbon is defined as a porous carbonaceous material with a carbon content ranging from 85 to 95%, which is generally obtained through a high-temperature heating process of carbon-rich materials (Musthapa et al., 2023). In the present study, activated carbon was synthesized from durian peel waste obtained from fruit sellers in the South Ring area of Cilegon City. The utilization of durian peel as a raw material for adsorbent production was based on its considerably high lignocellulosic content, including cellulose, hemicellulose, and lignin, which enables its conversion into porous carbon material (Wangkawong et al., 2024). Furthermore, the use of biomass waste as a precursor for activated carbon is considered a more sustainable approach, as it increases the added value of organic waste while simultaneously reducing environmental pollution.

The synthesis process of activated carbon was carried out through dehydration, carbonization, and activation stages, with quality parameters referring to the Indonesian National Standard (SNI 06-3730-1995). The dehydration stage was performed to reduce the moisture content of the biomass prior to the carbonization process. Durian peel was cut into small pieces to enlarge the contact surface area during drying, then dried under sunlight for 3–5 days until a dry sample condition was achieved. This process was followed by oven drying to further reduce the moisture content of the material. The dehydration stage plays an important role because high water content can inhibit the carbonization process and cause excessive smoke and ash formation during heating (Wangkawong et al., 2024). The reduction of moisture content also contributes to improving the efficiency of carbon structure formation during the pyrolysis process.

The carbonization stage was conducted at 400°C under limited oxygen conditions to convert biomass into carbonaceous material. During this process, thermal decomposition of lignocellulosic components occurred, resulting in the release of volatile compounds such as hydrocarbons, tar, methanol, and acetic acid, thereby leaving a more stable carbon matrix (Chitpreecha et al., 2026). Carbonization temperature was found to influence pore formation and the amount of carbon produced. The use of 400°C in this study was selected because it was able to produce carbon with a reasonably good structure without causing pore damage due to excessively high temperatures. Throughout the carbonization process, a color change of the sample from brown to black indicated the formation of a carbon structure, which was attributed to an increase in fixed carbon content and a decrease in volatile components.

The carbonization results showed a carbon yield of 11.50%, with an obtained carbon weight of 202.20 g. The relatively low yield indicated that most of the organic components in durian peel underwent decomposition during the carbonization process. This condition suggests that the pyrolysis process was effective in removing volatile substances and producing a material with higher carbon content ((Damayanti et al., 2023). Carbon yield was influenced by several factors, including biomass type, particle size, initial moisture content, carbonization temperature, and heating duration. Generally, the higher the carbonization temperature, the lower the carbon yield, due to the increased degradation of organic compounds into gases and volatile vapors (J. Wang, 2005). However, this decrease in yield is typically accompanied by an improvement in activated carbon quality, particularly in terms of surface area and pore formation of the adsorbent. The synthesized activated carbon is shown in Figure 1.

Figure 1. Synthesized Activated Carbon

3.2. Activation of Carbon Using Lemon Extract

The activation process was aimed at enlarging and opening carbon pores through the cleavage of hydrocarbon bonds and oxidation of molecules on the carbon surface, thereby resulting in changes to the physical and chemical properties of the material, particularly an increase in surface area and the number of active sites, which affect adsorption capacity (Amin et al., 2023). In the present study, durian peel carbon was activated using a natural activator in the form of lemon fruit extract. The use of lemon extract was selected as a more environmentally friendly alternative activator compared to synthetic chemical activators because lemon contains various organic acid compounds, especially citric acid, ascorbic acid, malic acid, and oxalic acid, which are able to assist the pore formation process in carbon. Lemon extract was obtained from lemon flesh juice with a yield of 20.89% and a total volume of 640 mL (Zahr et al., 2023).

The carbonized carbon that had been ground was weighed at 15 g, then 100 mL of lemon extract was added at concentration variations of 25, 50, 75, and 100%. The mixture was stirred using a magnetic stirrer for 1 hour to enhance contact between the activator and the carbon surface, then filtered using Whatman No. 41 filter paper. The obtained carbon was subsequently dried at 60°C until dry activated carbon was produced.

Activation using lemon extract occurred through the interaction of organic acid compounds with the surface of carbonized carbon. The carboxylate groups (-COOH) in citric acid were able to dissolve mineral residues and non-carbon compounds still covering the carbon surface, thereby causing the carbon pores to become more open. The acidic condition during the activation process also accelerated the degradation of remaining hemicellulose, cellulose, and lignin that had not been completely decomposed during the carbonization stage. This process led to the formation of a more developed pore structure and increased the surface area of the activated carbon. In addition to enlarging pore volume, the presence of oxygen functional groups from organic acid compounds also increased the number of active sites on the adsorbent surface, so that the interaction between the adsorbent and metal ions became more optimal (L. Wang et al., 2025).

Increasing the concentration of lemon extract resulted in a more intensive activation process because the number of organic acid compounds interacting with the carbon surface became greater. This condition supported the formation of an adsorbent with a more open pore structure and better adsorption capacity for Cu^{2+} ions. The use of lemon extract as a natural activator also demonstrated a more sustainable approach, as it was able to reduce the use of synthetic chemicals that are corrosive and potentially generate hazardous residues.

3.3. Initial Characterization of Non-Activated Carbon and Activated Carbon

Initial characterization was performed to evaluate the quality of activated carbon produced by lemon extract activation based on parameters of the Indonesian National Standard (SNI 06-3730-1995), including moisture content, ash content, and iodine adsorption capacity. These parameters were used to determine the quality of the adsorbent and its relationship to metal adsorption capacity.

3.4. Moisture Content Test

Moisture content is defined as a parameter indicating the hygroscopic properties of activated carbon toward water molecules. A low moisture content value indicates that the pores of activated carbon are not significantly occupied by water, so that the active sites of the adsorbent are more available for the adsorption process. The results of moisture content analysis of non-activated carbon and activated carbon are presented in Table 1.

Table 1. Moisture Content Analysis Results of Durian Peel Activated Carbon

Activator Concentration (%)	Moisture Content (%)
0	14
25	10
50	8
75	4
100	2

Based on Table 1, the moisture content of activated carbon ranged from 2–14%, and all samples met the SNI 06-3730-1995 standard, which requires less than 15%. Non-activated carbon showed the highest moisture content of 14%, while activated carbon with 100% lemon extract concentration had the lowest moisture content of 2%. The decrease in moisture content with increasing lemon extract concentration indicated that organic acid activation was able to enhance pore opening and reduce the water content bound to the carbon surface. This condition caused the surface area of activated carbon to increase, so that adsorption sites became more available (Novianty, 2025).

3.5. Ash Content Test

Ash content indicates the amount of inorganic mineral residues remaining after the combustion process. High ash content can reduce adsorbent quality because it causes pore blockage and reduces the surface area of activated carbon. The results of ash content analysis are presented in Table 2.

Table 2. Ash Content Analysis Results of Durian Peel Activated Carbon

Activator Concentration (%)	Ash Content (%)
0	14
25	8
50	6
75	4
100	4

The analysis results showed that the ash content of activated carbon ranged from 4–14%. Activated carbon activated with lemon extract met the SNI 06-3730-1995 standard (<10%), whereas non-activated carbon had an ash content of 14% and therefore did not meet the quality standard. The decrease in ash content with increasing lemon extract concentration indicated that the organic acid compounds in lemon were able to dissolve mineral residues and inorganic compounds on the carbon surface. Low ash content indicated that the carbon pores were more open, so that adsorption capacity could be increased (S., 2021). The high ash content in non-activated carbon was influenced by the mineral content in the raw material as well as the carbonization process, which had not yet optimally resulted in carbon formation (Novianty, 2025).

3.6. Iodine Adsorption Capacity Test

Iodine adsorption capacity was used to evaluate the adsorption capacity of activated carbon toward small molecules and to describe the development of the microporous structure of the adsorbent. Iodine number determination was carried out using an iodometric titration method. The results of the iodine adsorption capacity test are presented in Table 3.

Table 3. Iodine Adsorption Capacity of Durian Peel Activated Carbon

Activator Concentration (%)	Iodine Adsorption Capacity (mg/g)
0	824.85
100	888.30

The test results showed that both non-activated carbon and activated carbon met the SNI 06-3730-1995 standard, with iodine adsorption capacity above 750 mg/g. However, activated carbon activated using lemon extract showed an increase in iodine adsorption capacity to 888.30 mg/g compared to non-activated carbon at 824.85 mg/g. This increase indicated that activation using lemon extract was able to enlarge the surface area and open carbon pores through the interaction of organic acid compounds with impurity residues on the carbon surface (Susmanto et al., 2020). The greater the iodine adsorption capacity produced, the better the quality of the activated carbon as an adsorbent, because it indicated a higher number of micropores and active sites. The reaction occurring during the iodine adsorption process on durian peel adsorbent is shown in the equation below:

$$I_2 + 2Na_2S_2O_3 \rightarrow 2NaI + Na_2S_4O_6$$

3.7. Adsorption of Cu^{2+} Ions and ICP-OES Analysis

The activated carbon produced from the activation process was subsequently applied to the adsorption process of Cu^{2+} ions with contact time variations of 15, 30, and 45 minutes. The contact time variation was performed to determine the optimum time for the adsorbent to adsorb metal ions until equilibrium conditions were reached. The adsorption process was carried out by mixing non-activated carbon and activated carbon into a Cu^{2+} solution, then stirred using a magnetic stirrer to optimize contact between the adsorbent and adsorbate. After the adsorption process was completed, the filtrate was analyzed using ICP-OES to determine the final concentration of Cu^{2+} ions, while the adsorbent after adsorption was dried and further characterized using SEM-EDX.

Characterization using ICP-OES was employed to determine the residual concentration (C_e) of Cu^{2+} ions after adsorption. Based on the ICP-OES results, the adsorption capacity (q, mg g^{-1}) was calculated using the equation $q = (C_0 - C_e)V/m$, while the Cu^{2+} removal efficiency (%) was calculated using $(C_0 - C_e)/C_0 \times 100$. The adsorption capacity and removal efficiency values are presented as the mean ± standard deviation (n = 2), and the adsorption capacity is illustrated in Table 3 and Figure 2 using error bars representing the standard deviation.

Table 3. Adsorption capacity (q) and removal efficiency of Cu^{2+} adsorption under different activation concentrations and contact times (mean ± SD, n = 2).

Lemon extract concentration	Contact time (min)	q (mg g^{-1})	Removal efficiency (%)
0%	15	0.906 ± 0.003	58.10 ± 0.19
0%	30	0.954 ± 0.002	61.17 ± 0.15
0%	45	1.100 ± 0.003	70.52 ± 0.16
25%	15	1.554 ± 0.000	99.61 ± 0.01
25%	30	1.548 ± 0.002	99.24 ± 0.15
25%	45	1.551 ± 0.001	99.47 ± 0.06
50%	15	1.546 ± 0.001	99.10 ± 0.04
50%	30	1.552 ± 0.000	99.53 ± 0.01
50%	45	1.542 ± 0.002	98.87 ± 0.11
75%	15	1.550 ± 0.001	99.37 ± 0.05
75%	30	1.547 ± 0.001	99.16 ± 0.04
75%	45	1.549 ± 0.001	99.29 ± 0.05
100%	15	1.467 ± 0.003	94.08 ± 0.18
100%	30	1.505 ± 0.002	96.47 ± 0.13
100%	45	1.547 ± 0.001	99.19 ± 0.06

Values are presented as mean ± standard deviation (n = 2). Adsorption capacity (q) was calculated using $q = (C_0 - C_e)V/m$.

Tabel 4. Comparison of adsorption performance of biomass-derived adsorbents reported in previous studies

Adsorbent	Activator / Treatment	Target Pollutant	Adsorption Performance	Reference
Durian peel bioadsorbent	None	Fe and Zn	Fe removal: 15.0%; Zn removal: ~100% (Zn < 0.001 mg L^{-1})	Ariyani et al. (2019)
Activated carbon from durian peel	Carbonization	COD	q = 690 mg g^{-1}; COD removal = 68.2%	Musthapa et al.
Activated carbon from durian peel	KOH (25%)	BOD, COD, TSS	Activated carbon exhibited optimum removal of BOD, COD, and TSS in tofu wastewater treatment*	Ridhayanti & Rusmini (2020)
Green mussel treated with starfruit extract	Natural citric acid	Fe and Co	Fe removal = 64.87%; Co removal = 73.81%	Widiyanto et al. (2023)
Activated carbon activated with lemon extract (This study)	Natural citric acid (25%)	Cu^{2+}	q = 1.554 ± 0.000 mg g^{-1}; Removal = 99.61 ± 0.01%	This study

The calculated adsorption capacity showed that activated carbon prepared using 25% lemon extract exhibited the highest adsorption capacity of 1.554 ± 0.000 mg g^{-1} after 15 min of contact time, corresponding to a Cu^{2+} removal efficiency of 99.61 ± 0.01%. This result indicates that acid activation using lemon extract successfully enhanced the adsorption performance by providing sufficient accessible active sites for Cu^{2+} binding. Comparison with previous studies on fruit peel-derived adsorbents (Table 4) demonstrates that the Cu^{2+} removal efficiency obtained in this study is among the highest reported, highlighting the effectiveness of lemon extract as a natural activating agent Although slight fluctuations in adsorption capacity were observed with increasing contact time and activator concentration, the q values remained relatively stable after the initial adsorption stage, suggesting that adsorption equilibrium had been reached within the investigated contact time.

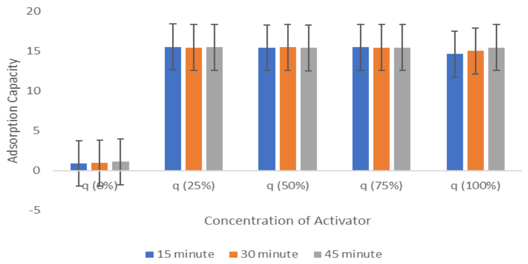

Figure 2. Graph of Cu2+ Ion Adsorption Capacity

Contact time is considered an important factor in the adsorption process because it is directly related to the rate of interaction between the adsorbent and metal ions. In the initial stage of adsorption, the number of vacant active sites caused Cu^{2+} ions to be bound more quickly to the adsorbent surface. The adsorption capacity reached a high value within the first 15 min, indicating rapid occupation of the available adsorption sites. Further increasing the contact time to 30 and 45 min produced only minor changes in adsorption capacity, suggesting that most of the accessible active sites had already interacted with Cu^{2+} ions and the adsorption process approached equilibrium. This observation is consistent with the small differences in q values obtained at longer contact times, indicating that extending the adsorption time beyond the equilibrium point provided no significant improvement in adsorption performance (Budi Ariyani, 2019).

The high adsorption capacity of activated carbon was influenced by the activation process using lemon extract, which is rich in organic acids, especially citric acid. Acid activation caused deprotonation of the carbon surface, resulting in the formation of negatively charged groups such as COO^- and O^-, which are active toward Cu^{2+} metal ions. These active groups played a role in forming complex interactions with Cu^{2+} ions, thereby increasing the adsorption capacity of the adsorbent (B. Wang et al., 2023; Widiyanto et al., 2023). In addition, the activation process also enlarged and opened the carbon pores, so that the surface area of the adsorbent increased and more active sites became available for the adsorption process. The reaction mechanism of Cu metal adsorption onto the adsorbent is shown in Figure 3.

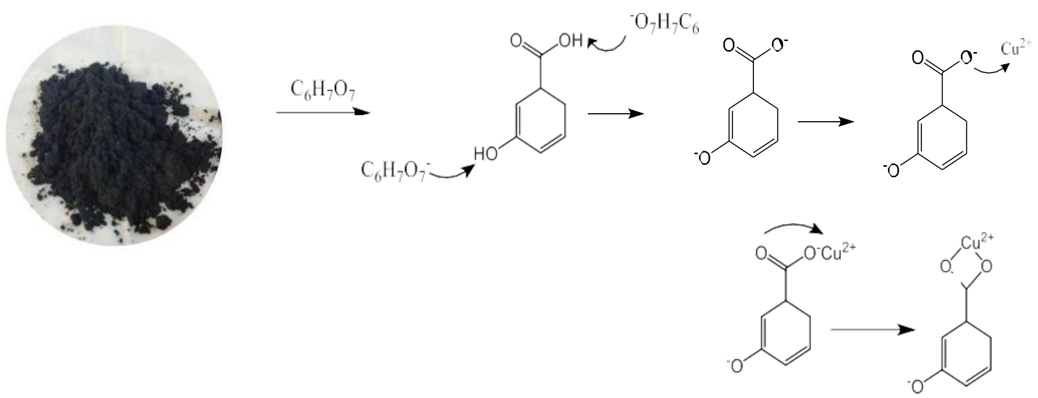

Figure 3. Reaction Mechanism of Cu Metal Adsorption onto the Adsorbent

3.8. Adsorption Kinetics and Mechanism

To elucidate the solute uptake rate and the underlying mass transfer mechanism, the duplicate experimental data were fitted into the linear forms of pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models. The linear regression analysis revealed that the adsorption process was significantly better described by the PSO model (R^2 = 0.9838 – 1.0000) than the PFO model (R^2 = 0.0581 - 0.9300) across all variations.

The extremely low R^2 values for the PFO model in the activated samples indicate that the initial metal uptake did not follow a slow, diffusion-controlled logarithmic trend. Instead, the calculated equilibrium adsorption capacities from the PSO model (1,23 - 1,69 mg g^{-1}) precisely aligned with the experimental values ($q_{e,exp}$), with the 25% lemon extract activator reaching a peak calculated capacity of 1.5501 mg g^{-1} against the experimental value of 1.5536 mg g^{-1}. This superior fit strongly implies that the rate-limiting step is predominantly governed by chemisorption, involving valence forces through electron sharing or exchange between Cu^{2+} ions and the carbon surface functional groups.

The chemical interaction was driven by the deprotonation of organic acids from the lemon extract, particularly citric acid, which successfully generated highly active oxygen-containing surface functional groups such as carboxylate (-COO-) and hydroxyl (-OH). These functional groups acted as specific coordination and electrostatic attraction sites that triggered robust complexation with Cu^{2+} ions, working synergistically with the enlarged pore structure to facilitate rapid adsorption during the initial contact phase.

However, it is crucial to note that this kinetic evaluation was strictly conducted within a single-solute (non-competitive) matrix. In realistic industrial wastewater applications, various co-existing heavy metal cations typically compete for the exact same vacant active sites on the carbon surface, which may alter the overall adsorption behavior. Consequently, further multi-component competitive adsorption studies are highly mandatory to comprehensively evaluate the true selectivity index and practical applicability of this lemon extract-activated carbon under real-world wastewater conditions.

3.9. Morphological Characterization of Activated Carbon Using SEM-EDX

Characterization using SEM was performed to observe changes in surface morphology and pore structure of activated carbon before and after activation. The SEM image results showed a fairly clear morphological change after the activation process using lemon extract. Before activation, carbon still showed many impurities covering the carbon surface and pores, whereas after activation, the activated carbon exhibited a cleaner surface with a more open and developed pore structure. The formation of pores with larger sizes indicated that activation using lemon extract was able to remove non-carbon residues and assist in the formation of a more porous adsorbent structure. The SEM image results are shown in Figure 4.

The pore diameter of the obtained activated carbon ranged from 12.1–15.8 μm, which was larger compared to non-activated carbon with a range of 9.42–12.6 μm. This increase in pore size indicated that the activation process was able to enlarge the surface area of the adsorbent, so that the diffusion process of Cu^{2+} ions into the carbonpores occurred more effectively. The larger and more open the pore structure of the adsorbent, the higher its adsorption capacity, because the adsorbate can more easily interact with active sites on the carbon surface (Qi et al., 2023). After the adsorption process, the SEM images showed that some pore cavities appeared more closed and filled with adsorbate material, indicating that Cu^{2+} ions had been successfully adsorbed onto the activated carbon surface.

Characterization using EDX showed the presence of a Cu spectral peak after the adsorption process with an atomic percentage of 0.67%, accompanied by a carbon content of 93.49% and an oxygen content of 5.84%. The detection of Cu on the activated carbon surface confirmed that Cu^{2+} ions had been successfully adsorbed into the pore structure of the adsorbent. A pre-adsorption EDX spectrum was not available for direct qualitative comparison because elemental analysis was performed only after the adsorption experiment. Nevertheless, the observed Cu signal, together with the substantial decrease in Cu^{2+} concentration determined by ICP-OES and the corresponding SEM observations, consistently supports the successful adsorption of Cu^{2+} onto the activated carbon surface. These results reinforced the ICP-OES data and SEM images, indicating that durian peel activated carbon activated using lemon extract possessed good adsorption capacity toward Cu^{2+} metal ions. The EDX graph after contact with copper metal is shown in Figure 5.

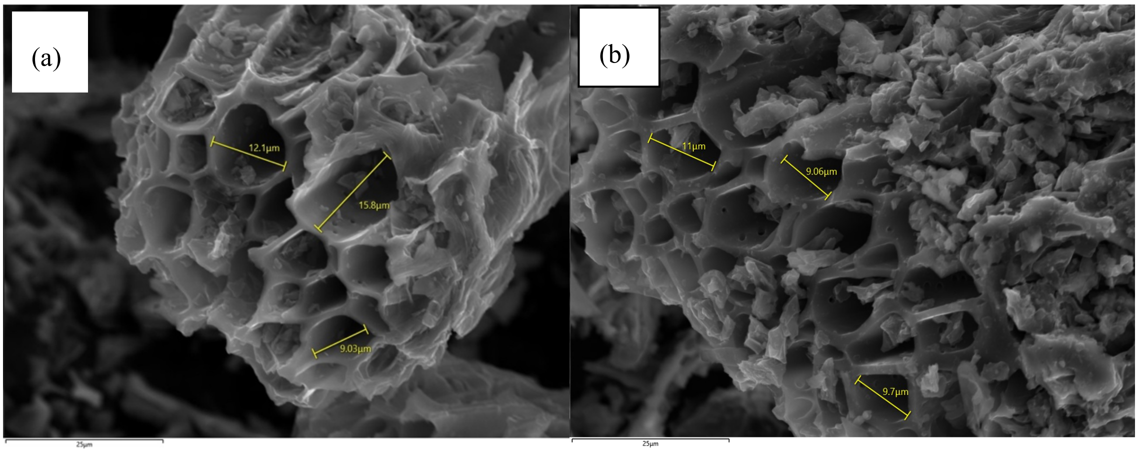

Figure 4. Carbon Diameter of Durian Peel (a) Non-Activated Carbon Diameter, and (b) Activated Carbon Diameter from Durian Peel

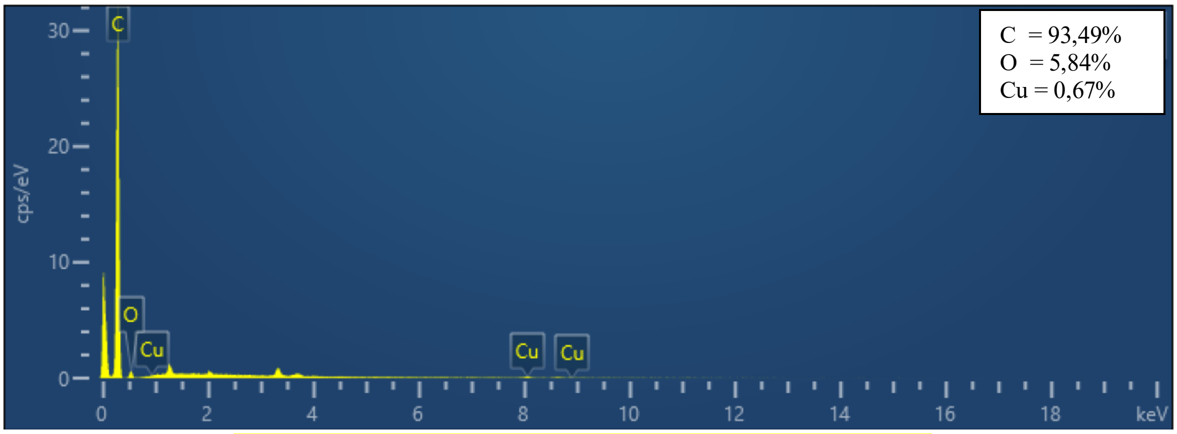

Figure 5. EDX Graph After Contact with Copper Metal

3.10. Statistical Analysis

Statistical analysis was performed to evaluate the effects of activator concentration and contact time on the adsorption efficiency of Cu^{2+} ions. The normality test using the Kolmogorov–Smirnov method showed a significance value of 0.080 (>0.05), indicating that the data were normally distributed. Meanwhile, the homogeneity test using the Levene method showed a significance value of 0.000 (<0.05), which indicated that the data were not homogeneous. Nevertheless, two-way ANOVA could still be performed because the main assumption that must be met was normal distribution of the data.

The ANOVA results showed a significance value of 0.000 (<0.05), indicating that variations in activator concentration and contact time had a significant effect on the adsorption efficiency of Cu^{2+} ions. These results suggest that the activation process using lemon extract, as well as the duration of interaction important role in determining the adsorption capacity of the activated carbon. Furthermore, the interaction between activator concentration and contact time demonstrated that the effect of contact time depended on the level of lemon extract used during the activation process. This interaction was reflected in the different adsorption trends observed among treatments. The non-activated carbon exhibited a gradual increase in adsorption efficiency from 58.10% at 15 min to 70.52% at 45 min, indicating that adsorption proceeded slowly because of the limited number of available active sites. In contrast, activated carbons prepared with 25–75% lemon extract reached adsorption efficiencies above 99% within the first 15 min and remained nearly constant with prolonged contact time, indicating that adsorption equilibrium was achieved rapidly after activation. These findings suggest that acid activation not only increased the number of accessible adsorption sites but also accelerated the adsorption kinetics by facilitating faster interactions between Cu^{2+} ions and the functional groups on the carbon surface.

The LSD post-hoc test showed that the contact time parameter had significant differences among treatments, as did most variations in activator concentration. All pairwise comparisons among contact times (15, 30, and 45 min) showed significant differences ($p < 0.001$), confirming that contact time significantly influenced the adsorption process. For activator concentration, almost all treatment pairs were significantly different ($p < 0.05$). However, no significant differences were observed between the 25% and 50% activator concentrations ($p = 0.556$) or between the 25% and 75% concentrations ($p = 0.124$), indicating that increasing the lemon extract concentration beyond 25% did not significantly improve Cu^{2+} removal efficiency. This finding agrees with the adsorption capacity results, in which the 25% activator concentration exhibited the highest adsorption performance. Therefore, the optimum activator concentration was considered to be 25%, as further increases in activator concentration did not produce statistically significant improvements in adsorption efficiency despite slight numerical variations.

4. CONCLUSION

Durian peel waste was successfully converted into activated carbon and demonstrated excellent potential as an environmentally friendly adsorbent for Cu^{2+} removal after activation using lemon extract as a natural activating agent. The activation process improved the physicochemical properties of the adsorbent, as evidenced by lower moisture and ash contents and higher iodine adsorption values that complied with the requirements of SNI 06-3730-1995. SEM-EDX analysis further confirmed the development of a more porous surface morphology and verified the presence of Cu on the adsorbent surface after adsorption, indicating successful metal uptake. The optimum adsorption performance was achieved using 25% lemon extract with a 15 min contact time, resulting in an adsorption capacity of 1.554 ± 0.000 mg g^{-1} and a Cu^{2+} removal efficiency of $99.61 \pm 0.01\%$.

Kinetic analysis showed that the adsorption process was better described by the pseudo-second-order model than the pseudo-first-order model, suggesting that chemisorption predominantly governed the adsorption mechanism. Furthermore, two-way ANOVA demonstrated that both activator concentration and contact time, as well as their interaction, significantly influenced the adsorption performance ($p < 0.05$), indicating that the effectiveness of contact time depended on the concentration of lemon extract used during activation. These findings demonstrate that lemon extract-activated carbon derived from durian peel is a promising, sustainable, and low-cost adsorbent for heavy metal remediation in aqueous systems. Nevertheless, this study was limited to single-component Cu^{2+} solutions and did not include BET surface area analysis or FTIR characterization; therefore, future studies should investigate adsorption behavior in multi-metal systems and perform comprehensive physicochemical characterization to better elucidate the adsorption mechanism and evaluate the applicability of the adsorbent under practical wastewater treatment conditions.

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