KONVERSI
Homepage:
https://ppjp.ulm.ac.id/journal/index.php/konversi

Adsorption behavior of Cu(II) on microwave-activated lemongrass-derived carbon: Isotherm and kinetic modeling

Lailan Ni`mah[1,*], Mahfud Mahfud[2], Sri Rachmania Juliastuti[2], Ramdiana Muis[3,4]

[1]*Chemical Engineering Department, Engineering Faculty, Lambung Mangkurat University, Banjarbaru 70714, Indonesia*
[2]*Department of Chemical Engineering, Faculty of Industrial Technology, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia*
[3]*Department of Urban and Regional Planning, Universitas Muhammadiyah Pare-pare, Pare-pare 91131, Indonesia*
[4]*Graduate Programs in Environmental Systems, Graduate School of Environmental Engineering, The University of Kitakyushu, Kitakyushu 808-0135, Japan*

ARTICLE INFO

Article history:

Received: 19 February 2026
Received in revised form: 17 April 2026
Accepted: 17 April 2026

Keywords:

Microwave activated carbon;
lemongrass derived adsorbent;
heavy metal adsorption; adsorption isotherms;
kinetic modeling

ABSTRACT

This study investigates the adsorption behavior of Cu(II) ions using microwave-activated carbon derived from lemongrass biomass as a low-cost and sustainable adsorbent for acid mine drainage (AMD) treatment. Unlike conventional thermal activation methods, microwave irradiation offers rapid and energy efficient heating that can enhance pore development and surface characteristics of lignocellulosic carbon materials. The precursor was initially carbonized at 300°C for 2 h and subsequently activated using microwave irradiation to improve its physicochemical properties. Batch adsorption experiments were conducted at adsorbent dosages of 2–7 g with a fixed contact time of 60 min, and residual Cu concentrations were measured using atomic absorption spectrophotometry. The optimum dosage of 4 g achieved the highest removal efficiency of 54.18%. Adsorption equilibrium data were evaluated using Langmuir and Freundlich isotherm models, with the Langmuir model providing a better fit, indicating monolayer adsorption on relatively homogeneous active sites. The maximum adsorption capacity (q_{max}) was 3.60 mg/g with a Langmuir constant (K_L) of 43.27 L/mol and R^2 of 0.9825, compared with K_F of 3.46 and R^2 of 0.9677 for the Freundlich model. Kinetic analysis showed that the adsorption process follows a pseudo-second-order model, suggesting that the rate of Cu(II) uptake is influenced by surface interaction mechanisms. The results demonstrate that microwave-activated lemongrass carbon has potential as an environmentally friendly adsorbent material and contributes to the development of rapid activation strategies for biomass-based carbon in AMD treatment applications.

1. Introduction

Environmental contamination, particularly from mining activities, poses a significant threat to ecosystem stability. Acid mine drainage (AMD) is especially concerning due to its low pH and elevated concentrations of heavy metals and sulfates, such as iron, manganese, copper, cadmium, lead, and nickel. The high acidity and metal content of AMD can lead to the pollution of surface water, groundwater, and soil, creating hazards for plants, wildlife, aquatic organisms, and human health. Copper (Cu), an essential heavy metal, is required in trace amounts but exhibits toxicity when accumulated beyond biological tolerance levels. Excessive exposure to Cu can result in gastrointestinal disturbances, including abdominal pain, nausea, vomiting, and diarrhea, and in severe cases, may cause kidney failure or death [1,2].

A variety of strategies have been developed for the treatment of wastewater containing heavy metals, including chemical precipitation, ion exchange, membrane filtration, electrochemical techniques, electrodialysis, biological treatments, and adsorption. Among these approaches, adsorption has emerged as the most widely employed method due to its operational simplicity, high removal efficiency, and cost-effectiveness [3].

Adsorption is commonly described as an interfacial phenomenon in which attractive interactions promote the attachment of a solute species (adsorbate) onto the surface of a solid phase (adsorbent) until thermodynamic equilibrium is established, at which point no further net uptake occurs [4]. This process may also be interpreted as the development of one or more adsorbate layers on the adsorbent surface, predominantly governed by van der Waals interactions. Fundamentally, adsorption entails the preferential accumulation of adsorbate molecules at the solid–liquid or solid–gas interface relative to their concentration in the surrounding bulk phase [5]. Adsorbents employed in this process are typically characterized by a porous structure and a high specific surface area, which together facilitate enhanced interaction with the target species [6,7]. As outlined by Gasparetto et al. [8], the overall adsorption mechanism proceeds through several sequential steps, including mass transfer of solute molecules from the bulk phase to the external surface of the adsorbent (external diffusion), transport within the internal pore structure (intraparticle diffusion), migration along the adsorbent surface (surface diffusion), and the elementary adsorption–desorption events occurring at active sites.

* Corresponding author. Tel.: +6281251562219
Email: lailan.nimah@ulm.ac.id.
http://dx.doi.org/10.20527/k.v15i1.25556

Activated carbon is widely recognized as an effective adsorbent for the removal of metal ions from contaminated effluents [9,10]. In addition to its demonstrated affinity toward inorganic pollutants, it exhibits strong adsorption capacity for a broad range of organic compounds [11,12]. From a practical perspective, activated carbon can be produced in a cost-effective manner, particularly when derived from abundant and renewable biomass residues [13,14]. Among these, lemongrass waste represents a promising precursor due to its relatively high cellulose content [32], which constitutes an essential structural component for the development of porous carbon materials [15,16]. To provide a clearer perspective on the current state of biomass-based adsorbents for Cu(II) removal, Table 1 summarizes representative studies reported in the literature, allowing identification of performance trends as well as remaining challenges related to adsorption capacity optimization.

Table 1. Comparison of Cu(II) adsorption capacity of various biomass-based adsorbents

Biomass precursor	Activation method	q_{max} (mg/g)	Reference
Arenga pinnata fruit shell	KOH+ ultrasound	11.77	[17]
Sewage sludge carbon	H_3PO_4+ microwave	7.73	[18]
Agricultural waste biochar	thermal pyrolysis	5–45 (range)	[19]
Corn straw hydrochar	PEI functionalization	56.1	[20]
Biochar (various biomass)	Pyrolysis	5–30 (typical range)	[21]
Red algae activated carbon	chemical activation	~18–35	[22]
Lemongrass-derived carbon (this work)	microwave activation	3.60	This study

Table 1 presents a comparison of the maximum adsorption capacity (q_{max}) of Cu(II) using various biomass-based adsorbents reported in the literature. The results indicate that adsorption capacity varies widely depending on precursor composition, activation method, and experimental conditions. Although the q_{max} obtained in this study (3.60 mg/g) is lower than some chemically activated carbons, the microwave activation approach offers advantages in terms of rapid processing time, lower energy consumption, and environmentally friendly preparation method. These characteristics highlight the potential of lemongrass biomass as a sustainable precursor for low-cost adsorbent production.

Activated carbon is a modified carbonaceous material distinguished by its high capacity to adsorb substances from both liquid and gaseous phases and may be produced from a wide range of carbon-rich precursors of organic or inorganic origin [13]. The development of its adsorption properties is achieved through activation processes, which are generally classified as chemical or physical in nature. Chemical activation involves the impregnation of a carbon precursor with specific activating agents to promote bond cleavage and pore development, whereas physical activation relies on high-temperature treatment in the presence of inert or oxidizing gases, such as nitrogen, steam, or CO_2, to enhance porosity and surface area. In addition to these conventional approaches, microwave irradiation has emerged as an effective alternative for activated carbon production. As reported by Huang et al. [23], microwave heating represents a promising substitute for traditional high-temperature methods, offering rapid and controllable heating as well as improved energy efficiency. Originally developed in the mid-twentieth century and widely adopted for domestic applications due to its fast heating rates, microwave technology was later extended to industrial material processing, where its advantages became increasingly recognized prior to the 1990s [23]. Microwave heating, also referred to as dielectric heating, enables the direct conversion of electromagnetic energy into thermal energy within the material, thereby allowing volumetric and uniform heating with deeper penetration compared to conventional external heat sources [24]. As a result, microwave-assisted activated carbon typically exhibits enhanced textural properties, including increased pore density, enlarged pore dimensions, and cleaner pore structures, relative to untreated lemongrass waste. Moreover, the uniform activation achieved through microwave irradiation contributes to improved adsorption performance, rendering this method particularly attractive for advanced adsorption applications [24]. Microwave-assisted activation has attracted increasing attention due to its rapid and energy-efficient heating mechanism, which can promote devolatilization and pore development in lignocellulosic biomass [25]. The adsorption performance of biomass-derived carbon materials is strongly influenced by surface area, pore structure, and the presence of oxygen-containing functional groups such as hydroxyl, carbonyl, and carboxyl groups, which can serve as active sites for metal ion binding [26]. Therefore, understanding adsorption behaviour through isotherm and kinetic modelling is an important preliminary step in evaluating the feasibility of microwave-activated carbon for AMD treatment [27]. In this context, activation assisted by microwave irradiation offers an efficient approach to enhance pore development and surface characteristics, thereby improving the overall adsorption performance of the resulting carbon material.

Adsorption kinetics represents a critical parameter in determining the efficiency and performance of a sorption process, as it characterizes both the rate at which solute species are captured and the residence time of adsorbates at the solid–liquid interface. The adsorption rate is fundamentally influenced by the frequency of particle attachment to the adsorbent surface per unit time, as well as the rate of collisions between solute particles and available adsorption sites within a given surface area [28]. This kinetic perspective provides essential insight into the dynamic behavior of adsorption systems and underpins the optimization of adsorbent design and operational conditions for enhanced removal efficiency.

Adsorption isotherms provide a fundamental framework for characterizing the interactions between adsorbates and adsorbents, offering critical insights into the efficiency and capacity of the adsorption process. They serve as essential tools for determining the maximum adsorption capacity of an adsorbent and for evaluating its practical applicability in specific systems [29]. By quantifying the amount of adsorbate accumulated on the adsorbent surface as a function of its concentration in the surrounding solution, isotherms enable the rational design and optimization of adsorption systems, ensuring effective performance under the intended operational conditions.

Although various lignocellulosic biomasses have been investigated as precursors for activated carbon, studies integrating microwave activation approach, physicochemical characterization, and adsorption evaluation under AMD-relevant conditions remain scarce, particularly for lemongrass-derived carbon materials.

2. Materials and Methods

2.1. *Materials and equipments*

The precursor material employed for the synthesis of activated carbon was lemongrass plant residue (*Cymbopogon* sp.), which was sourced from South Kalimantan. Analytical-grade CuSO solutions used in the adsorption experiments were procured from Merck. The experimental setup included a crusher, an oven dryer (Memmeth DIN12880-KI), a conventional furnace (SX-2.8-12, BocHuanghua Faitful Instrument Co., Ltd.), a tubular furnace, a microwave unit, an analytical balance (Shimadzu AW-220), and a sieving system equipped with an 850-micron mesh tray. Microwave-assisted preparation of activated carbon was conducted using an Electrolux microwave oven (model EMM20K22BA), manufactured by Electrolux (Hangzhou) Domestic Appliances Co., Ltd., Hangzhou, Zhejiang Province, China.

2.2. Methods

2.2.1. Preparation process of activated carbon

The lemongrass waste (*Cymbopogon* sp.) was initially subjected to a thorough cleaning procedure to remove adhering dirt and impurities. The cleaned material was then cut into smaller fragments and crushed using a crusher to obtain particle sizes of approximately 1–2 cm. Subsequently, the material was dried in an oven at 105 °C for 24 hours. Following the drying step, the waste was carbonized in a furnace (SX-2.8-12, Boc Huanghua Faitful Instrument Co., Ltd.) at 300 °C for 2 hours. The resulting carbon was further processed in a microwave (Electrolux model EMM20K22BA) at 400 W for 10 minutes. This microwave treatment at 400 W yielded activated carbon with larger, cleaner, and more abundant pores compared to samples treated at 500 W and 600 W, as well as a higher carbon content. The adsorbent employed comprised technical-grade activated carbon, representing 10 % of the total mass subjected to microwave treatment [30]. Prior to the activation process, nitrogen gas was purged through the system to minimize oxidation and ensure the integrity of the material.

2.2.2. Evaluation of adsorption isotherms

Activated carbon, prepared from lemongrass waste and conforming to established quality standards, was employed to remove Cu^{2+} ion from acid mine drainage. Varying amounts of the adsorbent (2–7 g) were introduced into 100 mL of the metal-containing solution, and the mixtures were gently agitated at 50 rpm for 60 minutes to ensure equilibrium. After filtration through Whatman 42 paper, the concentrations of residual metal ions were quantified using atomic absorption spectrophotometry, and the adsorption capacity was calculated in mg/g. The experimental data were then fitted to the Langmuir and Freundlich models to characterize the adsorption isotherms, providing a clear and comprehensive evaluation of the adsorbent's performance in wastewater treatment.

The adsorption capacity of the activated carbon was determined, and the corresponding adsorption isotherms were developed using the Langmuir and Freundlich models [31]. These models were employed to calculate the amount of Cu ion adsorbed (Q_e) in each experimental trial.

$$Q_e = \frac{(C_0 - C_e)V}{W} \quad (1)$$

The adsorption capacity (Q_e, mg/g) of the activated carbon was determined by relating the initial (C_0, mg/L) and equilibrium (C_e, mg/L) concentrations of Fe, Cu, and Mn in the solution. The calculation accounted for both the volume of the acid mine drainage (V, L) and the mass of the adsorbent (W, g), providing a precise measure of metal ion uptake and facilitating the subsequent development of adsorption isotherms [31].

Eq. (2) describes the conditions of the Langmuir isotherm model.

$$q = q_{max}\left(K_L \frac{C_e}{1 + K_L C_e}\right) \quad (2)$$

In this context, q(mg/g) represents the amount of heavy metal ions adsorbed per unit mass of the adsorbent, while K_L is the Langmuir equilibrium constant, reflecting the affinity of the adsorbent toward the available binding sites. C_e denotes the equilibrium concentration of Ni^{2+} ions in solution, and q_{max} corresponds to the theoretical maximum adsorption capacity for a monolayer coverage [31]. This formulation provides a quantitative basis for evaluating the adsorption efficiency and characterizing the interaction between the adsorbate and the adsorbent.

The Freundlich isotherm model describes adsorption occurring on a heterogeneous surface, leading to a quantifiable equilibrium state [31].

$$q_e = K_F C_e^{\frac{1}{n}} \quad (3)$$

In this model, q_e represents the adsorption capacity (mg/g), C_e denotes the equilibrium concentration of the adsorbate in solution (mg/L), and K_F and n are empirical constants that describe the adsorption capacity and the intensity of the process, respectively.

All adsorption experiments were performed under carefully controlled conditions to evaluate Cu(II) removal behaviour of microwave-activated lemongrass carbon. Experimental procedures including adsorbent dosage, contact time, and measurements using calibrated atomic absorption spectrophotometry were standardized to ensure consistent results. While standard deviation (±SD) and error bars were not calculated in this preliminary study, observed trends in adsorption capacity and removal efficiency were reproducible under these conditions. Future work will incorporate experimental replication and statistical analysis to provide a more rigorous quantitative assessment of variability.

2.2.3. Evaluation of adsorption kinetic behavior

Activated carbon, prepared to meet established quality standards, was employed as an adsorbent for the treatment of

acid mine drainage containing Cu^{2+}, Fe^{3+}, and Mn^{2+} ions. In this study, 4 g of agricultural waste-derived activated carbon was added to 100 mL of the wastewater sample, initially containing 25.61 ppm $CuSO_4$, in individual Erlenmeyer flasks. The suspensions were agitated using a rotary shaker at 50 rpm for varying contact times of 15, 30, 45, 60, 75, and 90 minutes. Following agitation, the mixtures were filtered through Whatman 42 filter paper, and the filtrates were analyzed for metal ion concentrations using atomic absorption spectrophotometry, with the initial solutions measured in the same manner. The adsorption capacity was calculated in mg/g, and the adsorption kinetics were evaluated by fitting the experimental data to both pseudo first order and pseudo second order models.

The pseudo first order (PFO) model, also referred to as the Lagergren model [38], is represented by the following Eq. 4.

$$ln\ ln\left(q_e - q_t\right) = ln\left(q_e - k_1 t\right) \quad (4)$$

The pseudo second order (PSO) or Lagergren model [32][39] is expressed by the following Eq. 5.

$$\frac{\mathbf{1}}{\boldsymbol{q_t}} = \frac{\mathbf{1}}{\boldsymbol{k_2 q_e^2}} + \frac{\boldsymbol{t}}{\boldsymbol{q_e}} \quad (5)$$

3. Results and Discussion

3.1. Impact of adsorbent amount on the adsorption of Cu ions from acid mine drainage

The adsorption performance of lemongrass-derived activated carbon was further assessed using atomic absorption spectrophotometry (AAS) to quantify the residual concentrations of Cu, Fe, and Mn in acid mine drainage after treatment. As summarized in Table 2, at a contact time of 60 minutes, the activated carbon demonstrated significant removal efficiencies for all metals. The results indicate that Cu^{2+} ions were effectively adsorbed onto the activated carbon surface, highlighting the material's potential as a low-cost and efficient adsorbent for heavy metal remediation.

Table 2. Atomic absorption spectrophotometry (AAS) results for Cu

Parameter	Activated Carbon Mass (g)	Results (mg/L)
Cu	Initial Solution	25.61
	2	23.94
	3	23.48
	4	23.00
	5	22.98
	6	22.96
	7	22.95

The adsorption performance of lemongrass-derived activated carbon was further evaluated by measuring the residual Cu concentration in acid mine drainage using atomic absorption spectrophotometry (AAS). As presented in Table 2, these results provide a quantitative assessment of the material's efficiency in removing copper ions under the applied experimental conditions, offering insights into the effectiveness of adsorbent dosage and contact time on Cu uptake.

Referring to Figures 1, the maximum removal efficiencies for Fe and Mn were achieved at an optimal adsorbent dosage of 4 g. Beyond this dosage, further increases in removal efficiency were minimal, reflecting the intrinsic limitations of the adsorbent [40]. Figures 1 demonstrate that the percentage of metal removal generally increases with higher adsorbent mass, primarily due to the expansion of available adsorption sites and surface area, which enhances metal uptake at elevated doses. Nevertheless, excessively high adsorbent amounts may promote aggregation, thereby reducing the effective surface area and slightly limiting removal efficiency [32]. Furthermore, increasing the adsorbent mass enhances the adsorption rate by providing more active sites for metal ions, allowing for greater interaction and capture of cations from the solution. Overall, a higher adsorbent-to-contaminant ratio contributes to improved pollutant removal efficiency [25].

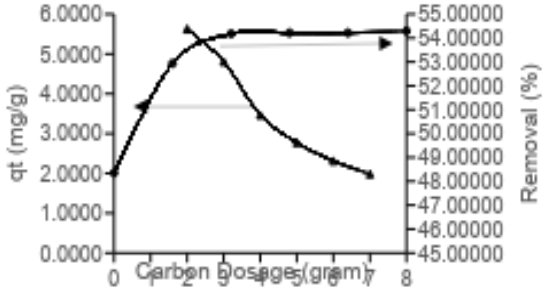

Fig. 1. Effect of lemongrass-derived activated carbon dosage on Cu removal

Referring to Fig.1, the maximum removal efficiencies for Cu were achieved at an optimal adsorbent dosage of 4 g. Beyond this dosage, further increases in removal efficiency were minimal, reflecting the intrinsic limitations of the adsorbent. The percentage of metal removal generally increases with higher adsorbent mass, primarily due to the expansion of available adsorption sites and surface area, which enhances metal uptake at elevated doses. Moreover, the observed increase in metal removal with higher adsorbent mass can also be attributed to the development of pore structure during microwave activation, which enhances the accessibility of adsorption sites. This structural evolution facilitates greater interaction between Cu^{2+} ions and the adsorbent surface, particularly under conditions relevant to acid mine drainage [33].

Nevertheless, excessively high adsorbent amounts may promote aggregation, thereby reducing the effective surface area and slightly limiting removal efficiency [34]. Furthermore, increasing the adsorbent mass enhances the adsorption rate by providing more active sites for metal ions, allowing for greater interaction and capture of cations from the solution. Overall, a higher adsorbent-to-contaminant ratio contributes to improved pollutant removal efficiency [35].

The observed increase in metal removal with higher adsorbent mass can also be attributed to the development of pore structure during microwave activation, which enhances

the accessibility of adsorption sites. This structural evolution facilitates greater interaction between Cu^{2+} ions and the adsorbent surface, particularly under conditions relevant to acid mine drainage. Microwave-assisted activation may influence the development of pore structure by generating rapid internal heating, which promotes the removal of volatile components and the formation of micro- and mesopores within the carbon matrix. The presence of these pores increases the accessible surface area and facilitates the diffusion of Cu(II) ions from the bulk solution to the internal adsorption sites. The pore network formed during activation plays an important role in determining adsorption performance because it controls the accessibility of active sites and reduces mass transfer resistance. Although surface area characterization was not extensively investigated in this study, lignocellulosic biomass such as lemongrass typically produces carbon structures containing microporous domains that contribute to adsorption capacity [36]. However, excessively high dosages may lead to particle aggregation, which reduces the effective surface area and slightly limits removal efficiency [37]. Furthermore, a higher adsorbent mass enhances the adsorption rate by providing more active sites for metal ion interactions, thereby capturing a larger proportion of cations from the solution. Overall, an increased adsorbent-to-contaminant ratio contributes to improved efficiency in pollutant removal [30].

3.2. Effect of contact time on the removal of Fe and Mn from acid mine drainage using activated carbon

The effect of contact time on Cu adsorption from acid mine drainage using lemongrass-derived activated carbon was evaluated. As the contact duration increased, Cu removal efficiency improved, indicating progressive interaction between the adsorbent and copper ions. Maximum removal was observed at an optimal contact time of 60 minutes, while further extension resulted in negligible improvement, suggesting that adsorption equilibrium had been attained (Fig. 2).

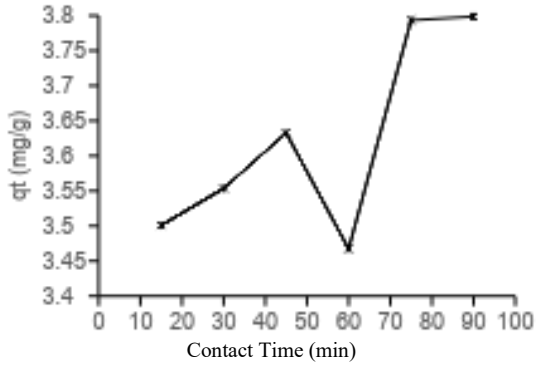

Fig. 2. Effect of contact time on Cu removal using lemongrass-derived activated carbon

As illustrated in Fig. 2, the adsorption of Cu increases markedly during the initial 15–60 minutes before reaching a plateau beyond 60 minutes. Maximum adsorption is observed at 60 minutes, indicating that the adsorption capacity rises significantly within this interval prior to attaining equilibrium. This behavior is attributed to the gradual saturation of available active sites on the adsorbent as contact time progresses. At extended contact times, such as 90 minutes, the adsorption rate declines due to full site occupation. Furthermore, once the activated carbon reaches saturation, prolonged exposure may lead to partial desorption, resulting in the release of previously adsorbed metal ions back into the solution [38].

3.3. Evaluation of adsorption isotherms for lemongrass-derived activated carbon in the treatment of acid mine drainage

The adsorption isotherm data for lemongrass-derived activated carbon in the treatment of acid mine drainage were systematically analyzed to evaluate the equilibrium behavior and adsorption capacity of the material. Both Langmuir and Freundlich isotherm models were applied to interpret the experimental data.

The Langmuir model provided a better fit, indicating monolayer adsorption on relatively homogeneous active sites. This behavior can be explained by the presence of oxygen-containing functional groups, such as hydroxyl, carboxyl, and carbonyl groups, which originate from the lignocellulosic lemongrass biomass and contribute to Cu^{2+} binding through electrostatic attraction and surface complexation. The uniform pore structure developed during microwave activation further supports the formation of well-distributed active sites, facilitating efficient monolayer adsorption. In contrast, the Freundlich model represents adsorption on heterogeneous surfaces and was used to assess adsorption intensity and favorability. The 1/n value below 1 confirms that adsorption is favorable, but overall, the Langmuir model more accurately describes the adsorption equilibrium (Table 3).

Table 3. Calculated adsorption isotherm parameters for Cu using Langmuir and Freundlich Models

Langmuir Equation			Freundlich Equation		
q_{max} (mg/g)	K_L (mol/L)	R^2	K_F (mol/L)	1/n	R^2
3.60	43.27	0.9825	3.60	0.000012	0.9677

The Langmuir model provided a better fit, indicating monolayer adsorption on relatively homogeneous active sites. This behavior can be explained by the presence of oxygen-containing functional groups, such as hydroxyl, carboxyl, and carbonyl groups, which originate from the lignocellulosic lemongrass biomass and contribute to Cu^{2+} binding through electrostatic attraction and surface complexation. The uniform pore structure developed during microwave activation further supports the formation of well-distributed active sites, facilitating efficient monolayer adsorption [39].

The adsorption equilibrium of Cu(II) ions on microwave-activated lemongrass carbon was analyzed using both Langmuir and Freundlich models to provide insight into surface characteristics and adsorption mechanisms. The Langmuir model showed a better fit ($R^2 = 0.9825$), suggesting that the adsorption sites are relatively homogeneous and that Cu(II) uptake occurs predominantly via monolayer coverage. The Langmuir constant ($K_L = 43.27$ L/mol) reflects the affinity between Cu(II) ions and the available adsorption sites; a relatively high K_L value indicates strong binding interactions, implying that the active sites are energetically favorable for Cu(II) adsorption. The maximum adsorption capacity (q_{max} = 3.60 mg/g) represents the theoretical monolayer coverage, providing an estimate of the number of available adsorption sites per unit mass of adsorbent.

The Freundlich model also provided a reasonable fit (R^2 =

0.9677), capturing the slight surface heterogeneity inherent to lignocellulosic biomass. The Freundlich constant K_F = 3.46 mg/g represents adsorption capacity under heterogeneous surface conditions, while 1/n < 1 indicates favorable adsorption, with higher affinity at lower Cu(II) concentrations. Comparison of both models suggests that while the surface is largely homogeneous, some heterogeneity exists due to variations in pore size and distribution of oxygen-containing functional groups formed during microwave activation.

Overall, the combined interpretation of Langmuir and Freundlich parameters indicates that Cu(II) adsorption on lemongrass carbon is primarily driven by energetically favorable surface interactions, with minor contributions from heterogeneous sites. This more detailed analysis provides a mechanistic understanding linking adsorption performance to surface site availability and energetic characteristics of the adsorbent.

The adsorption of heavy metals using lemongrass-derived activated carbon was evaluated through Langmuir and Freundlich isotherm models, as presented in Table 3. The Langmuir model provided a better fit, indicating monolayer adsorption on a homogeneous surface. Maximum adsorption capacities (q_{max}) were 3.60 mg/g for Cu, reflecting saturation of the adsorbent's surface at higher concentrations. In the Freundlich model, 1/n values below 1 confirm that adsorption is favorable, yet the overall data align more closely with the Langmuir isotherm. Coefficients of determination (R^2) approaching unity further support the assumption of uniform adsorption sites, where metal ions are adsorbed in a monolayer fashion. These findings highlight the efficiency of lemongrass derived activated carbon in removing Cu from acid mine drainage and provide insight into the equilibrium characteristics governing the adsorption process.

Although the maximum adsorption capacity (q_{max}) obtained in this study (3.60 mg/g) is relatively lower compared to some chemically activated carbons reported in the literature, this value remains scientifically relevant when considering the activation approach, material sustainability, and application context. Many high adsorption capacities are achieved through intensive chemical activation using strong activating agents such as KOH, H_3PO_4, or $ZnCl_2$, which may increase production cost and generate secondary environmental impacts due to chemical consumption and post-treatment requirements. In contrast, the present study applies microwave-assisted activation as a rapid and energy-efficient alternative, minimizing chemical usage and processing time while maintaining measurable adsorption performance.

Furthermore, adsorption capacity is not solely determined by precursor type but also influenced by experimental conditions such as initial metal concentration, solution pH, adsorbent dosage, and contact time. The adsorption experiment in this study was conducted within a relatively short contact time (60 min) and dosage range (2–7 g), which may limit the maximum adsorption capacity but provides practical insight into operationally feasible conditions for real treatment systems.

It is also important to note that adsorption performance should be evaluated not only based on qmax, but also on material accessibility, preparation simplicity, economic feasibility, and environmental sustainability. Lemongrass biomass is an abundant lignocellulosic residue that is widely available and underutilized, making it a promising precursor for low-cost adsorbent production. The use of microwave activation provides an advantage in terms of rapid heating and potentially lower energy consumption compared to conventional furnace activation, supporting the development of sustainable carbon materials.

Therefore, the findings of this study contribute to the growing body of knowledge on environmentally friendly adsorbent synthesis strategies, particularly in exploring the potential of microwave-assisted activation to convert agricultural biomass into functional carbon materials for Cu(II) removal under conditions relevant to acid mine drainage treatment.

3.4. Kinetic evaluation of adsorption using lemongrass-derived activated carbon for acid mine drainage treatment

This section addresses the kinetic behavior of heavy metal adsorption onto lemongrass-derived activated carbon from acid mine drainage. The study investigates the rate at which Cu ions are removed, providing insights into the adsorption mechanism and the time-dependent interaction between the adsorbent and the metal ions. By applying kinetic models such as pseudo-first-order and pseudo-second-order equations, the adsorption process can be quantitatively described, enabling the assessment of reaction rates and the prediction of equilibrium times for efficient heavy metal remediation. The kinetic parameters were derived by plotting the equations for each model, it can be seen in Table 4 below:

Table 4. Kinetic parameters of Cu adsorption using activated carbon

PFO			PSO		
q_e (mg/g)	k_1	R^2	q_e (mg/g)	k_2	R^2
3.4674	43.2619	0.8659	3.4700	3.4498	0.9538

The adsorption kinetics of Cu(II) on microwave-activated lemongrass carbon were evaluated using both pseudo-first-order (PFO) and pseudo-second-order (PSO) models. The experimental data showed a better fit with the PSO model (R^2 = 0.9538) compared to the PFO model (R^2 = 0.8659), indicating that the adsorption process is more accurately described by pseudo-second-order kinetics. This suggests that the rate-limiting step is likely chemical adsorption involving electron sharing or exchange between Cu(II) ions and functional groups on the carbon surface. The PSO model assumes that the adsorption rate depends on both the availability of adsorption sites and the interaction strength between adsorbate and adsorbent.

The kinetic results are consistent with the equilibrium data, which were best described by the Langmuir isotherm model, indicating monolayer adsorption on relatively homogeneous sites. Although the PFO model may describe initial adsorption trends at low Cu(II) concentrations, the overall adsorption behaviour is governed by surface interactions and site occupancy, supporting the conclusion that chemical interactions dominate the adsorption process. The relatively moderate adsorption capacity suggests that further optimization of microwave parameters—such as irradiation power, activation time, or the addition of activating agents—could enhance pore development and improve adsorption performance in future studies [40].

The observed adsorption behaviour can be further explained

by the physicochemical modifications induced during microwave-assisted activation. Microwave irradiation enables rapid internal heating of biomass through dipole rotation and ionic conduction mechanisms, which accelerate devolatilization and structural transformation of lignocellulosic components such as cellulose, hemicellulose, and lignin [41]. These processes contribute to the development of porous structures and the formation of oxygen-containing functional groups, which enhance accessibility of adsorption sites and facilitate interaction with Cu(II) ions.

Although detailed characterization such as BET surface area and functional group analysis was not performed in this study, the relatively good agreement with the Langmuir model and PSO kinetics suggests the presence of energetically favorable adsorption sites on the carbon surface [42], [43]. These findings provide preliminary evidence that microwave-assisted activation can improve the adsorption properties of lemongrass-derived carbon, highlighting its potential as a low-cost and environmentally friendly adsorbent for AMD treatment.

Future work should focus on comprehensive physicochemical characterization, including BET surface area, pore size distribution, and identification of surface functional groups, to establish a clearer relationship between pore structure development and adsorption performance. Optimization of microwave parameters and investigation under practical treatment conditions will further improve the efficiency and applicability of this sustainable biomass-based carbon for heavy metal remediation.

3.5. Adsorption performance of Cu(II) onto microwave-activated lemongrass-derived carbon

The adsorption performance of Cu(II) onto microwave-activated lemongrass-derived carbon is influenced by the physicochemical characteristics of lignocellulosic carbon materials, including pore structure, surface chemistry, and accessibility of active adsorption sites. The utilization of microwave-assisted activation provides a distinct heating mechanism compared to conventional furnace-based activation. Microwave irradiation generates volumetric heating through dipole rotation and ionic conduction, enabling rapid internal heat transfer within the biomass matrix. This process accelerates devolatilization of organic components such as cellulose, hemicellulose, and lignin, facilitating structural rearrangement and formation of porous carbon frameworks. The release of volatile matter during carbonization may create micro and mesoporous domains that enhance surface accessibility and promote diffusion of Cu(II) ions from bulk solution into the internal pore structure of the adsorbent [44], [45].

Although detailed characterization such as BET surface area analysis or pore size distribution was not conducted in the present study, previous research has consistently reported that microwave-assisted activation promotes development of porous structures with relatively uniform heat distribution and shorter processing time compared to conventional heating methods. The presence of pore networks plays an essential role in adsorption systems because pore channels regulate mass transfer resistance and determine the accessibility of adsorption sites. Increased pore connectivity may facilitate diffusion of Cu(II) ions toward internal binding sites, thereby influencing adsorption capacity and equilibrium behavior.

In addition to pore structure, the adsorption mechanism is also affected by the surface chemistry of biomass-derived carbon materials. Lemongrass biomass is composed primarily of lignocellulosic components containing hydroxyl, carboxyl, and carbonyl functional groups. After carbonization and activation, residual oxygen-containing functional groups may remain on the carbon surface and act as active binding sites for metal ions. These polar functional groups may interact with Cu(II) ions through electrostatic attraction, ion exchange, or surface complexation mechanisms involving coordination between electron-donating oxygen atoms and positively charged metal ions [46], [47]. Under acidic conditions relevant to acid mine drainage systems, partial protonation of functional groups may occur; however, negatively charged surface sites may still contribute to Cu(II) binding through complexation interactions.

The effect of adsorbent dosage on Cu(II) removal indicates that increasing adsorbent mass enhances removal efficiency up to an optimum dosage of 4 g. This trend can be attributed to an increase in the number of available adsorption sites and surface area accessible for interaction with Cu(II) ions. At higher dosages, adsorption efficiency tends to stabilize, suggesting that equilibrium is reached due to limited availability of Cu(II) ions relative to adsorption sites. This behavior is commonly observed in adsorption systems where an excessive adsorbent dose results in aggregation of particles or overlapping of adsorption sites, thereby reducing effective surface area available for adsorption.

Equilibrium analysis shows that adsorption data are better described by the Langmuir isotherm model compared to the Freundlich model, suggesting that adsorption occurs predominantly as monolayer coverage on relatively homogeneous active sites. The Langmuir model assumes uniform adsorption energy and absence of interaction between adsorbed species, indicating that Cu(II) ions occupy specific localized sites distributed across the carbon surface [48]. The relatively good coefficient of determination (R^2 = 0.9825) supports the hypothesis that adsorption occurs through specific surface interactions rather than multilayer adsorption. The maximum adsorption capacity (q_{max}) of 3.60 mg/g observed in this study is comparable to other lignocellulosic-based adsorbents produced under mild activation conditions, suggesting that microwave activation can produce functional carbon materials with measurable adsorption performance while maintaining relatively simple preparation procedures.

Kinetic evaluation indicates that adsorption follows pseudo-first-order behavior, suggesting that the rate of Cu(II) uptake is influenced by availability of adsorption sites and concentration of solute in solution. At the initial stage of adsorption, a large number of vacant active sites are available, resulting in rapid adsorption of Cu(II) ions. As adsorption progresses, the number of available sites decreases, leading to reduced adsorption rate until equilibrium is achieved. The pseudo-first-order kinetic behavior may indicate that adsorption is influenced by diffusion processes and physical interactions occurring at the adsorbent surface [49]. This suggests that the adsorption mechanism may involve a combination of external mass transfer, pore diffusion, and surface interaction rather than purely chemical bonding.

Overall, the adsorption mechanism of Cu(II) onto microwave-activated lemongrass carbon may involve multiple simultaneous processes, including diffusion of Cu(II) ions into pore networks, electrostatic attraction between positively

charged Cu(II) ions and negatively charged surface sites, and surface complexation with oxygen containing functional groups. The combination of Langmuir equilibrium behavior and pseudo-first-order kinetics suggests that adsorption occurs primarily on accessible surface sites with relatively uniform adsorption energy. These findings support the potential use of microwave-activated lignocellulosic carbon as a low-cost adsorbent for removal of heavy metals from contaminated water systems.

Nevertheless, a more comprehensive understanding of the structure–performance relationship would benefit from additional physicochemical characterization such as BET surface area analysis, pore size distribution measurement, SEM imaging, FTIR spectroscopy, or XPS analysis to identify structural and chemical changes induced by microwave activation. Such analyses would provide direct evidence of pore development and functional group distribution responsible for Cu(II) binding. Therefore, future work should incorporate these characterization techniques to further elucidate adsorption mechanisms at the molecular level and optimize activation conditions to improve adsorption capacity.

4. Conclusion

This study demonstrates that lemongrass-derived activated carbon is an effective adsorbent for the removal of Cu(II) from acid mine drainage, with adsorption efficiency strongly influenced by adsorbent dosage and contact time, and optimal removal achieved at 4 g and 60 minutes, respectively. Equilibrium data were best described by the Langmuir isotherm model, indicating monolayer adsorption on energetically homogeneous sites, while kinetic analysis revealed a pseudo-second-order mechanism, suggesting that chemical interactions between Cu(II) ions and functional groups on the carbon surface dominate the adsorption process. Building on these findings, microwave-activated lemongrass carbon shows significant potential as a low-cost and environmentally friendly adsorbent, with microwave-assisted activation providing a rapid and energy-efficient route for enhancing pore development and surface functionalization. Although detailed characterization such as BET surface area and functional group analysis was not performed, the consistency between kinetic and equilibrium results indicates the presence of energetically favorable adsorption sites. Future work should focus on comprehensive physicochemical characterization, including BET surface area, pore size distribution, and identification of surface functional groups, to establish clearer correlations between pore structure development and adsorption performance, thereby guiding the optimization of this sustainable adsorbent for practical heavy metal remediation applications.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Ministry of Research, Technology, and Higher Education of the Republic of Indonesia.

References

[1] Y. G. Wibowo, et al., Recent advances in the adsorptive removal of heavy metals from acid mine drainage by conventional and novel materials: a review, *Bioresour. Technol. Rep.* 25 (2024) 101797.

[2] S. Varshney, M. Lundås, P. Siriyappagouder, T. Kristensen and P. A. Olsvik, Ecotoxicological assessment of Cu-rich acid mine drainage of Sulitjelma mine using zebrafish larvae as an animal model, *Ecotoxicol. Environ. Saf.* 269 (2024) 115796.

[3] Y. Fei and Y. H. Hu, Recent progress in removal of heavy metals from wastewater: a comprehensive review, *Chemosphere* 335 (2023) 139077.

[4] S. Saren, F. Miksik, S. Seo, T. Miyazaki and K. Thu, Evaluation and development of improved thermodynamic models for adsorbed phase properties in adsorption cycles, *Int. J. Heat Mass Transf.* 229 (2024) 125579.

[5] J. R. Jambeck, et al., Plastic waste inputs from land into the ocean, *Science* 347 (2015) 768–771.

[6] K. M. AlAqad, M. M. Abdelnaby, A. Tanimu, I. Abdulazeez and A. M. Elsharif, Adsorbent materials for water treatment: a review of current trends and future challenges, *Environ. Pollut. Manag.* 2 (2025) 1–13.

[7] Y. Mei, S. Zhuang and J. Wang, Adsorption of heavy metals by biochar in aqueous solution: a review, *Sci. Total Environ.* 968 (2025) 178898.

[8] H. Gasparetto, M. Schadeck Netto, G. L. Dotto and N. P. G. Salau, External and intraparticle mass transfer effects on the uptake of atrazine and 2,4-D onto hierarchical soybean hull activated carbon, *J. Environ. Chem. Eng.* 13 (2025) 119787.

[9] F. Parvin, N. M. Niloy, M. M. Haque and S. M. Tareq, Activated carbon as potential material for heavy metals removal from wastewater, *Emerg. Tech. Treat. Toxic Met. Wastewater* (2023) 117–130.

[10] P. W. Olupot, J. Wakatuntu, M. Turyasingura, J. Jjagwe, E. Menya and M. Okure, Optimization of heavy metal removal by activated carbon obtained as a co-product from fast pyrolysis of rice husks, *Results Mater.* 21 (2024) 100545.

[11] S. Satyam and S. Patra, Innovations and challenges in adsorption-based wastewater remediation: a comprehensive review, *Heliyon* 10 (2024) e29573.

[12] B. Barczak and K. Januszewicz, Advancing sustainable wastewater treatment with biomass-based highly porous activated carbon: insights into sorption mechanisms and efficiency, *J. Environ. Chem. Eng.* 13 (2025) 118041.

[13] S. Ullah, et al., Activated carbon derived from biomass for wastewater treatment: synthesis, application and future challenges, *J. Anal. Appl. Pyrolysis* 179 (2024) 106480.

[14] J. Fang, et al., A review of biomass-based carbon dioxide adsorbents research, *Particuology* 105 (2025) 104–122.

[15] L. Ni'Mah, S. R. Juliastuti and M. Mahfud, Microwave-assisted synthesis, characterization, and performance assessment of lemongrass-derived activated carbon for removal of Fe and Mn from acid mine drainage, *J. Renew. Mater.* 13 (2025) 2169–2190.

[16] Geetanjali and P. P. Kundu, Lemon grass derived porous carbon impregnated with $NiWO_4$ as anode electrocatalyst to improve energy output in single chambered microbial fuel cell, *Int. J. Hydrogen Energy* 62 (2024) 812–824.

[17] S. D. Said, et al., Adsorption of Cu(II) from aqueous solution on sonicated activated carbon prepared from Arenga pinnata Merr fruit shell waste: isotherm, kinetic and thermodynamic studies, *Environ. Res. Eng. Manag.* 79 (2023) 112–123.

[18] X. Wang, et al., Adsorption of copper (II) onto activated carbons from sewage sludge by microwave-induced phosphoric acid and zinc chloride activation, *Desalination* 278 (2011) 231–237.

[19] F. M. Pellera, et al., Adsorption of Cu(II) ions from aqueous solutions on biochars prepared from agricultural by-products, *J. Environ. Manage.* 96 (2012) 35–42.

[20] X. He, et al., Enhanced adsorption of Cu(II) and Zn(II) from aqueous solution by polyethyleneimine modified straw hydrochar, *Sci. Total Environ.* 778 (2021) 146116.

[21] E. Baltrėnaitė-Gedienė, T. Leonavičienė and P. Baltrėnas, Comparison of Cu(II), Mn(II) and Zn(II) adsorption on biochar using diagnostic and simulation models, *Chemosphere* 245 (2020) 125562.

[22] M. Isam, L. Baloo, A. Chabuk, A. Majdi and N. Al-Ansari, Optimization and modelling of Pb(II) and Cu(II) adsorption onto red algae (Gracilaria changii)-based activated carbon by using response surface methodology, *Biomass Convers. Biorefin.* 14 (2023) 16799–16818.

[23] J. Huang, G. Xu, Y. Liang, G. Hu and P. Chang, Improving coal permeability using microwave heating technology: a review, *Fuel* 266 (2020) 117022.

[24] Z. Kou, Z. Zhao, H. Li and X. Gao, A review of adsorption intensified by microwave irradiation from absorbent preparation to separation processes, *Chem. Eng. Process.* 184 (2023) 109300.

[25] W. Ao, et al., Microwave assisted preparation of activated carbon from biomass: a review, *Renew. Sustain. Energy Rev.* 92 (2018) 958–979.

[26] Q. Zhang, Z. Li, Z. Liu, Y. D. Prasetyatama, W. K. Oh and I. K. M. Yu, Microwave-assisted biorefineries, *Nat. Rev. Clean Technol.* 1 (2025) 269–287.

[27] G. Durán-Jiménez, J. Rodriguez, L. Stevens, E. T. Kostas and C. Dodds, Microwave pyrolysis of waste biomass and synthesis of micro-mesoporous activated carbons: the role of textural properties for CO_2 and textile dye adsorption, *Chem. Eng. J.* 488 (2024) 150926.

[28] R. Al-Muhtasib, S. Bhagyaraj, P. Sobolciak and I. Krupa, Recent advances in adsorption technology for water purification, *Curr. Adv. Nanomater. Wastewater Remediat.* (2026) 529–563.

[29] E. G. Söğüt and M. Gülcan, Adsorption: basics, properties, and classification, *Adsorpt. Adv. Nanoscale Mater. Appl. Environ. Remediat.* (2023) 3–21.

[30] L. Ni'mah, S. R. Juliastuti and M. Mahfud, One-stage microwave-assisted activated carbon preparation from langsat peel raw material for adsorption of iron, manganese and copper from acid mining waste, *Commun. Sci. Technol.* 8 (2023) 143–153.

[31] N. Ayawei, A. N. Ebelegi and D. Wankasi, Modelling and interpretation of adsorption isotherms, *J. Chem.* (2017) 1–11.

[32] S. H. Yuh, Citation review of Lagergren kinetic rate equation on adsorption reactions, *Scientometrics* 59 (2004) 171–177.

[33] S. Ayob, et al., A review on adsorption of heavy metals from wood-industrial wastewater by oil palm waste, *J. Ecol. Eng.* 22 (2021) 249–265.

[34] F. Mashkoor, A. Nasar, Inamuddin and A. M. Asiri, Exploring the reusability of synthetically contaminated wastewater containing crystal violet dye using Tectona grandis sawdust as a very low-cost adsorbent, *Sci. Rep.* 8 (2018) 1–17.

[35] J. Wang and X. Guo, Adsorption kinetic models: physical meanings, applications, and solving methods, *J. Hazard. Mater.* 390 (2020) 122156.

[36] M. Selvam S and B. Paramasivan, Microwave assisted carbonization and activation of biochar for energy-environment nexus: a review, *Chemosphere* 286 (2022) 131631.

[37] C. Cheng, et al., Microwave-assisted preparation and characterization of mesoporous activated carbon from mushroom roots by phytic acid activation, *J. Taiwan Inst. Chem. Eng.* 67 (2016) 532–537.

[38] D. O. Kra, N. B. Allou, P. Atheba, P. Drogui and A. Trokourey, Preparation and characterization of activated carbon based on wood (Acacia auriculeaformis, Côte d'Ivoire), *J. Encapsulation Adsorpt. Sci.* 9 (2019) 63–82.

[39] G. Hotová, V. Slovák, T. Zelenka, R. Maršálek and A. Parchaňská, The role of the oxygen functional groups in adsorption of copper (II) on carbon surface, *Sci. Total Environ.* 711 (2020) 135436.

[40] R. K. Mishra, B. Singh and B. Acharya, A comprehensive review on activated carbon from pyrolysis of lignocellulosic biomass: an application for energy and the environment, *Carbon Resour. Convers.* 7 (2024) 100228.

[41] L. Ke, et al., Microwave catalytic pyrolysis of biomass: a review focusing on absorbents and catalysts, *npj Mater. Sustain.* 2 (2024) 24.

[42] R. Alrowais, M. M. Abdel Daiem, B. M. Nasef and N. Said, Activated carbon fabricated from biomass for adsorption/bio-adsorption of 2,4-D and MCPA: kinetics, isotherms, and artificial neural network modeling, *Sustainability* 16 (2024) 299.

[43] G. Li, J. He and J. Yao, A review of recent advances in biomass-derived porous carbon materials for CO_2 capture, *C* 11 (2025) 92.

[44] A. C. Lua and T. Yang, Effect of activation temperature on the textural and chemical properties of potassium hydroxide activated carbon prepared from pistachio-nut shell, *J. Colloid Interface Sci.* 274 (2004) 594–601.

[45] K. Y. Foo and B. H. Hameed, Porous structure and adsorptive properties of pineapple peel based activated carbons prepared via microwave assisted KOH and K_2CO_3 activation, *Microporous Mesoporous Mater.* 148 (2012) 191–195.

[46] S. Babel and T. A. Kurniawan, Low-cost adsorbents for heavy metals uptake from contaminated water: a review, *J. Hazard. Mater.* 97 (2003) 219–243.

[47] A. Demirbas, Heavy metal adsorption onto agro-based waste materials: a review, *J. Hazard. Mater.* 157 (2008) 220–229.

[48] K. Y. Foo and B. H. Hameed, Insights into the modeling of adsorption isotherm systems, *Chem. Eng. J.* 156 (2010) 2–10.

[49] Y. S. Ho and G. McKay, Pseudo-second order model for sorption processes, *Process Biochem.* 34 (1999) 451–465.