



Optimized copper-functionalized carbon from *Lansium parasiticum* trunk for chloramphenicol removal from aqueous solution

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Abstract

Chloramphenicol (Cp), a toxic antibiotic, poses significant risks to human health and aquatic ecosystems when released into the environment. This study investigates the removal of Cp from aqueous solution using copper-functionalized activated carbon derived from *Lansium parasiticum* trunk (Cu-MFCLT). The adsorbent was synthesized via microwave-assisted CO₂ activation followed by copper(II) nitrate, (Cu(NO₃)₂) surface modification. Optimal synthesis conditions were identified through response surface methodology (RSM), yielding a radiation power of 466.24 W, a duration of 13 min, and a metal loading rate (MLR) of 0.60 g/g. Under these conditions, the predicted Cp uptake capacity of 71.19 mg/g closely matched the experimental value of 73.66 mg/g, with an error of 3.35%. For Cu-MFCLT yield, the predicted and actual yield values were 52.75% and 51.11%, respectively (error of 3.21%). High R² values of 0.9441 and 0.9392 confirmed the reliability of the RSM models for Cp uptake and Cu-MFCLT yield, respectively. The optimized Cu-MFCLT showed a BET surface area (BET-SA) of 866.86 m²/g and a mesopore surface area (MESO-SA) of 627.17 m²/g. Adsorption equilibrium followed the Langmuir model, indicating monolayer coverage with a maximum adsorption capacity, Q_m of 129.58 mg/g. Kinetic studies followed the pseudo-first-order (PFO) model, with k₁ values decreasing from 0.77 to 0.39 h⁻¹ as Cp concentration increased from 10 to 100 mg/L. After five regeneration cycles, thermal microwave regeneration reduced Cp removal to 10.85% and Cu-MFCLT yield to 4.45%, whereas ethanol solvent regeneration maintained 65.82% Cp removal and 73.52% Cu-MFCLT yield, confirming ethanol as the superior regeneration method.

Keywords Adsorption · Antibiotic · Microwave activation · Regeneration · Wastewater treatment

Introduction

As broad-spectrum antimicrobials, chloramphenicol (Cp) exhibits strong antibacterial activity against a wide range of bacterial strains, encompassing numerous Gram-negative and Gram-positive strains (Cheng et al. 2021). Since

the 1950s, Cp has been widely used due to its outstanding efficacy in both human and animal healthcare (Jiang et al. 2020). Typically, Cp is excreted largely in its unchanged form through excrement and urine due to incomplete biological metabolism in humans or animals (Yao et al. 2020). Hospital wastewater represents a major environmental pathway for Cp discharge. Owing to its extensive application in clinical settings, Cp concentrations in medical wastewater can reach several milligrams per liter (mg/L) (Nguyen et al. 2022). Incomplete removal of Cp during treatment results in its release into surrounding ecosystems, where it undergoes transformation into degradation byproducts through natural processes such as photodegradation, hydrolysis, and biological degradation. Some degradation byproducts are documented to be 5–15 times more toxic than their parent Cp compounds (Cotillas et al. 2018; Lin et al. 2022). Cp residue presence is widespread, appearing in hospitals, municipal systems, fish farming effluents, animal husbandry sites, and open water bodies spanning various nations and

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territories (Cheng et al. 2021). Significantly, Cp concentrations reaching several hundred to exceeding 1000 ng/L have been observed in wastewater discharges across the globe. Additionally, Cp has been linked to multiple harmful consequences affecting human well-being (e.g., impaired blood cell production and diminished bone marrow activity) and aquatic life (e.g., reduced growth and disrupted cellular metabolism in algae species) (Nguyen et al. 2022).

Given the persistence and toxicity of Cp in aquatic environments, the development of effective removal technologies has become an urgent research priority. Various technologies have been explored for antibiotic removal; however, conventional treatment methods often remain ineffective due to the poor biodegradability and persistence of these compounds in aquatic environments (Chen et al. 2022). For instance, constructed wetlands offer simplicity in operation and require minimal maintenance, but their large land demand limits practical implementation in urban areas (Alsubih et al. 2022; Mohamad et al. 2024). Coagulation and flocculation have long been standard practices in water treatment; however, they are now viewed as less effective in achieving current treatment benchmarks. These techniques often struggle to remove specific contaminants, especially micropollutants such as antibiotics, highlighting the demand for more advanced treatment approaches (Bury et al. 2023). Membrane processes have shown great potential in removing organic contaminants; however, they are challenged by issues of fouling and high operational costs (Matin et al. 2023). Semiconductor-driven photocatalysis is safe and durable; however, its effectiveness is hindered by rapid charge recombination, low photon efficiency, and particle clustering (Omar et al. 2024). Adsorption has emerged as a favoured wastewater treatment technique because of its simplicity, high efficiency, operational flexibility, and regenerability, while maintaining strong performance under toxic conditions. Previous studies have shown that the adsorption process is capable of eliminating diverse contaminants like synthetic dyes (Mohd Ramli et al. 2023), *p*-nitrophenol (Liu et al. 2025), diclofenac (Allahgholi et al. 2025), fluoride (Sivakumar et al. 2025), heavy metals (Yusop et al. 2022; Igberase et al. 2025), antibiotics (Nasran et al. 2023), and others.

Activated carbon (AC) is a highly effective adsorbent; however, growing environmental concerns have driven a shift away from coal-based precursors due to their adverse impacts on land, air, and water resources (Mohamad et al. 2025). Consequently, a wide range of biomass materials have been converted into AC as sustainable alternatives including olive stone (Massaoudi et al. 2024), durian seed (Ahmad et al. 2017), *Alpinia galanga* stem (Ahammad et al. 2021), Egyptian wood (Ilnicka et al. 2020), and so on. Biomass-derived AC generally possesses a high surface area, which largely drives its effectiveness in

adsorbate removal. To further enhance its performance, additional porosity can be achieved by raising activation temperatures, extending activation time, or using stronger chemical agents during chemical activation. However, these modifications often lead to higher costs and increased resource consumption.

An alternative strategy to boost AC performance is surface modification with metals, a process known as metal-functionalized carbon (MFC). For example, incorporating Cu^{2+} ions onto lemon peel-based AC has been shown to enhance amoxicillin removal by 38.93% (Mohamad et al. 2024), and incorporating Cu^{2+} ions onto rattan waste-based AC boosted Cp uptake by 30.40% (Mohamad et al. 2025). Therefore, in this study, the trunk of *Lansium parasiticum* was transformed into a copper(II)-functionalized carbon material by treating it with copper(II) nitrate, $\text{Cu}(\text{NO}_3)_2$. This modified carbon is designated as Cu-MFCLT, indicating its unique composition and enhanced adsorption properties imparted by the copper functionalization. *Lansium parasiticum* trunk was selected in this study due to the absence of prior reports on its utilization as an adsorbent precursor. Based on available literature, only *Lansium parasiticum* empty fruit bunch has been reported for adsorbent production (Njoku et al. 2015; Foo and Hameed 2012). The selection of *Lansium parasiticum* trunk is also attributed to its woody, hardwood nature, which is inherently associated with higher lignin content and enhanced structural integrity. Hardwood biomass decomposes gradually over a wide temperature range, promoting enhanced structural stability that makes hardwood-derived carbons suitable for adsorbent preparation and more resilient during regeneration processes (Đukanović et al. 2025).

The preparation conditions for Cu-MFCLT were fine-tuned by incorporating response surface methodology (RSM) through a central composite design (CCD). RSM offers several advantages, including its ability to evaluate multiple variables simultaneously, identify optimal conditions with fewer experimental runs, and provide insight into interactions between process parameters. This method enables a more efficient and systematic optimization process, reducing resource usage and experimental time while maximizing performance outcomes (Mohamad et al. 2025). In addition, the efficacy of the models developed can be further verified by analysis of variance (ANOVA) (Yusop et al. 2025). Three variables were selected for optimization: radiation power (W), radiation time (min), and metal loading rate (MLR, g/g). The responses evaluated in this study included the adsorption uptake for Cp (mg/g) and the yield percentage of Cu-MFCLT. All experiments and related work in this study were conducted from 1 February 2025 to 31 August 2025 at the Sustainable Waste Conversion Research Laboratory, School of Chemical Engineering, Universiti Sains Malaysia, Penang, Malaysia.



Materials and methods

Materials

The trunk of *Lansium parasiticum*, commonly referred to as the langsat trunk, was sourced locally from a fruit farm in Penang. During the preparation process, nitrogen gas (N_2) was used in the carbonization phase, while carbon dioxide (CO_2) was applied during the microwave activation step; both gases were supplied by MOX-Linde Gases Sdn. Bhd. Copper(II) nitrate ($Cu(NO_3)_2$), purchased from R&M Chemicals, had a molecular weight of 241.60 g/mol and a purity of 99%. Chloramphenicol (Cp, $C_{11}H_{12}Cl_2N_2O_5$; purity $\geq 98\%$) was purchased from Sigma-Aldrich and used without further purification. Ethanol (C_2H_5OH), purchased from R&M Chemicals, had a molecular weight of 46.07 g/mol and a purity of 95% and was used as the regeneration solvent without further purification.

Synthesis of Cu-MFCLT

The *Lansium parasiticum* trunk precursor was initially oven-dried for 48 h at 60 °C, then manually cut and sieved to obtain particle sizes between 2.0 and 2.5 cm, as shown in Fig. 1a. Then, the dried precursor was placed in a conventional vertical furnace (Model Carbolite, USA) and carbonized at 500 °C for 1.5 h, under the flow of N_2 gas at a flow rate of 150 cm³/min. The heating rate during carbonization was set at 10 °C/min. The produced char was subsequently activated using a microwave oven (EMM2021MW, Sweden) at a radiation power of 466.24 W and a radiation time of 13 min, under a CO_2 flow rate of 150 cm³/min to achieve physical activation. This treated material, referred to as pristine MFCLT, was then soaked in an ultrasonic washer containing 200 mL of copper (II) nitrate, $Cu(NO_3)_2$ solution at a metal loading rate (MLR) of 0.60 g/g to initiate metal functionalization. The ultrasonic washer was operated for 10 min, after which the resulting sample, labelled as Cu-MFCLT, was oven-dried for 48 h at 60 °C before being used in adsorption experiments. The dried Cu-MFCLT was sieved to obtain particle sizes between 1.0 and 1.5 cm, as shown in Fig. 1b.

The MLR and yield of adsorbents can be calculated as follows, respectively:

$$MLR\left(\frac{g}{g}\right) = \frac{m_{Cu(NO_3)_2}(g)}{m_{Cu-MFCLT}(g)} \quad (1)$$

where MLR (g/g) is the metal loading rate, $m_{Cu(NO_3)_2}(g)$ is the mass of $Cu(NO_3)_2$ used for metal functionalization, and $m_{Cu-MFCLT}(g)$ is the dry mass of the final Cu-MFCLT.

$$Yield(\%) = \frac{m_{Cu-MFCLT}(g)}{m_{precursor}(g)} \times 100 \quad (2)$$

where Yield (%) is the yield of Cu-MFCLT and $m_{precursor}(g)$ is the dry mass of the precursor before carbonization.

Optimization investigation

The optimization of process parameters was executed via Design Expert Software (version 12, STAT-EASE Inc., Minneapolis, USA). To achieve precise adjustments, a central composite design (CCD) strategy was implemented within by the Response Surface Methodology (RSM). This approach allowed for a thorough evaluation of variable interactions, enhancing the accuracy of parameter predictions and ensuring optimal process performance across various experimental conditions, focusing on three variables: radiation power (X_1), radiation time (X_2), and MLR (X_3), with two response measurements: Cp uptake (Y_1) and Cu-MFCLT yield (Y_2). The variables were tested at levels of +1, 0, and −1, corresponding to 264, 462, and 660 W for radiation power; 4, 12, and 20 min for radiation time; and 0.10, 0.55, and 1.0 g/g for MLR.

Batch adsorption experiments

In the batch equilibrium experiment, Cp solutions were prepared with initial concentrations, C_0 (mg/L), varying between 10 and 100 mg/L, each containing a total volume, V , of 200 mL. These solutions were subsequently positioned in a temperature-controlled bath shaker, meticulously maintained at a steady 30 °C with a consistent agitation speed of 80 rpm. A carefully weighed 0.20 g portion of adsorbent (W), either

Fig. 1 The image of **a** dried precursor before carbonization and **b** Cu-MFCLT



pristine MFCLT or Cu-MFCLT, was then introduced into each flask to facilitate the adsorption process and ensure uniform experimental conditions. At designated time points, the Cp concentration was analysed using a UV–Vis spectrophotometer (Agilent Cary 60, USA). This sampling lasted till the system reached equilibrium and the corresponding concentration was defined as the equilibrium concentration, C_e (mg/g). The quantity of Cp retained on the pristine MFCLT or Cu-MFCLT surface and the adsorption efficiency of Cp from the solution were determined using the equations below:

$$C_{\text{uptake}}, q_e \left(\frac{\text{mg}}{\text{g}} \right) = \frac{(C_o - C_v)V}{W} \quad (3)$$

$$\% \text{ Removal} = \frac{C_o - C_e}{C_o} \times 100\% \quad (4)$$

Isotherm investigation

An isotherm study is essential in adsorption research as it provides insights into how adsorbates interact with an adsorbent's surface at a constant temperature. This study helps determine the capacity of the adsorbent and the nature of the adsorption process, such as whether it is monolayer or multilayer, homogeneous or heterogeneous. Understanding these characteristics is crucial for optimizing adsorption systems, predicting performance, and scaling up for practical applications in wastewater treatment, environmental cleanup, and other fields where adsorption is used. The equilibrium data were subsequently fitted to various isotherm models, which are outlined in detail as follows:

Langmuir (Langmuir 1918):

$$q_e = \frac{Q_m K_L C_e}{1 + K_L C_e} \quad (5)$$

where q_e (mg/g) is the equilibrium adsorption capacity, Q_m (mg/g) is the maximum monolayer adsorption capacity, K_L (L/mg) is the Langmuir equilibrium constant related to adsorption affinity, and C_e (mg/L) is the equilibrium concentration of adsorbate in solution.

Freundlich (Freundlich 1906):

$$q_e = K_F C_e^{1/n_F} \quad (6)$$

where K_F ((mg/g)(L/mg)^{1/n_F}) is the Freundlich constant and n_F (dimensionless) is the heterogeneity factor.

Temkin (Temkin and Pyzhev 1940):

$$q_e = \frac{RT}{B_T} \ln (A_T C_e) \quad (7)$$

where A_T (L/mg) is the Temkin equilibrium binding constant and B_T (J/mol) is the Temkin constant related to adsorption heat.

Kinetic and mechanism investigation

Kinetic investigation and diffusion mechanisms are crucial in adsorption as they reveal the adsorption rate and controlling processes. Understanding these aspects helps optimize adsorbent efficiency, indicating whether surface interactions or intraparticle diffusion dominate the adsorption process. Two kinetic models were outlined as follows:

Pseudo-first order (PFO) (Lagergren 1898):

$$q_t = q_e [1 - \exp(-k_1 t)] \quad (8)$$

where q_t (mg/g) is the adsorption capacity at time t , k_1 (h⁻¹) is the pseudo-first-order rate constant and t (h) is the contact time.

Pseudo-second order (PSO) (Ho and Mckay 1998):

$$q_t = \frac{k_2 q_e^2 t}{1 + k_2 q_e t} \quad (9)$$

where k_2 (g/mg.h) is the pseudo-second-order rate constant.

An additional kinetic model, known as the Boyd plot, is employed to identify the rate-limiting step in the adsorption process. This model is given below:

$$B_t = -0.4977 - \ln \left(1 - \frac{q_t}{q_e} \right) \quad (10)$$

where B_t is the Boyd number.

Regeneration investigation

The regeneration of Cu-MFCLT saturated with Cp was performed through microwave activation and the solvent method using ethanol to evaluate the adsorbent's reusability. For microwave regeneration process, the spent Cu-MFCLT was reactivated by exposing it to microwave irradiation at 440 W for 10 min. Following this microwave treatment, the regenerated Cu-MFCLT was subsequently tested in further adsorption experiments with Cp to examine its adsorption efficiency and performance retention over multiple cycles. For the solvent regeneration method, the spent Cu-MFCLT was soaked in C₂H₅OH for 1 h, followed by filtration and oven-drying at 60 °C for 48 h before reuse in adsorption experiments. The experimental conditions utilized were 0.20 g of Cu-MFCLT and 200 mL of Cp solution with a concentration of 100 mg/L.



Results and discussion

Table 1 Thorough experimental design layout for Cu-MFCLT synthesis

Run	Synthesis variables			Responses	
	Radiation power, X_1 (Watt)	Radiation time, X_2 (min)	MLR, X_3	Cp uptakes, Y_1 (mg/g)	Cu-MFCLT yield, Y_2 (%)
1	264 (−1)	4 (−1)	1 (+1)	20.51	66.14
2	264 (−1)	12 (0)	0.55 (0)	33.21	51.45
3	462 (0)	12 (0)	1 (+1)	40.52	57.85
4	462 (0)	12 (0)	0.55 (0)	73.54	52.19
5	660 (+1)	4 (−1)	0.1 (−1)	70.86	30.08
6	660 (+1)	4 (−1)	1 (+1)	33.15	47.88
7	462 (0)	12 (0)	0.1 (−1)	67.45	45.29
8	462 (0)	20 (+1)	0.55 (0)	75.96	41.96
9	660 (+1)	20 (+1)	0.1 (−1)	95.55	21.85
10	462 (0)	4 (−1)	0.55 (0)	53.34	47.89
11	462 (0)	12 (0)	0.55 (0)	76.53	54.34
12	264 (−1)	20 (+1)	0.1 (−1)	44.61	33.65
13	660 (+1)	20 (+1)	1 (+1)	45.52	40.58
14	462 (0)	12 (0)	0.55 (0)	79.55	56.77
15	264 (−1)	20 (+1)	1 (+1)	32.5	60.11
16	264 (−1)	4 (−1)	0.1 (−1)	29.88	45.05
17	660 (+1)	12 (0)	0.55 (0)	69.96	34.63
18	462 (0)	12 (0)	0.55 (0)	70.11	50.42
19	462 (0)	12 (0)	0.55 (0)	81.75	58.49
20	264 (−1)	4 (−1)	1 (+1)	20.51	66.14

Adsorption optimization

Regression models

Table 1 exhibits the detailed experimental design framework devoted to optimizing the synthesis of Cu-MFCLT. This table shows the response values obtained for each combination of variables at coded values of + 1, 0, and − 1. For the Cp uptake response, the minimum and maximum values were 20.51 mg/g and 95.55 mg/g, respectively, while for Cu-MFCLT yield, the minimum and maximum values were 21.85% and 66.14%, respectively.

The software-selected quadratic models (expressed in coded factors) for the analysed responses are presented below:

Cp uptake (%), Y_1

$$Y_1 = 71.52 + 15.43X_1 + 8.64X_2 - 13.62X_3 - 13.97X_1^2 - 0.9037X_2^2 - 11.57X_3^2 + 1.29X_1X_2 - 8.28X_1X_3 - 1.88X_2X_3 \quad (11)$$

Cu-MFCLT yield (%), Y_2

$$Y_2 = 52.38 - 8.14X_1 - 3.89X_2 + 9.66X_3 - 6.76X_1^2 - 4.87X_2^2 + 1.77X_3^2 + 0.2375X_1X_2 - 1.38X_1X_3 + 0.7875X_2X_3 \quad (12)$$

Figure 2a and b show the regression plots for the estimated versus actual values of Cp uptake and Cu-MFCLT yield, respectively. The R^2 values for these plots were found to be 0.9441 for Cp uptake and 0.9392 for Cu-MFCLT yield, demonstrating a robust relationship between the forecasted

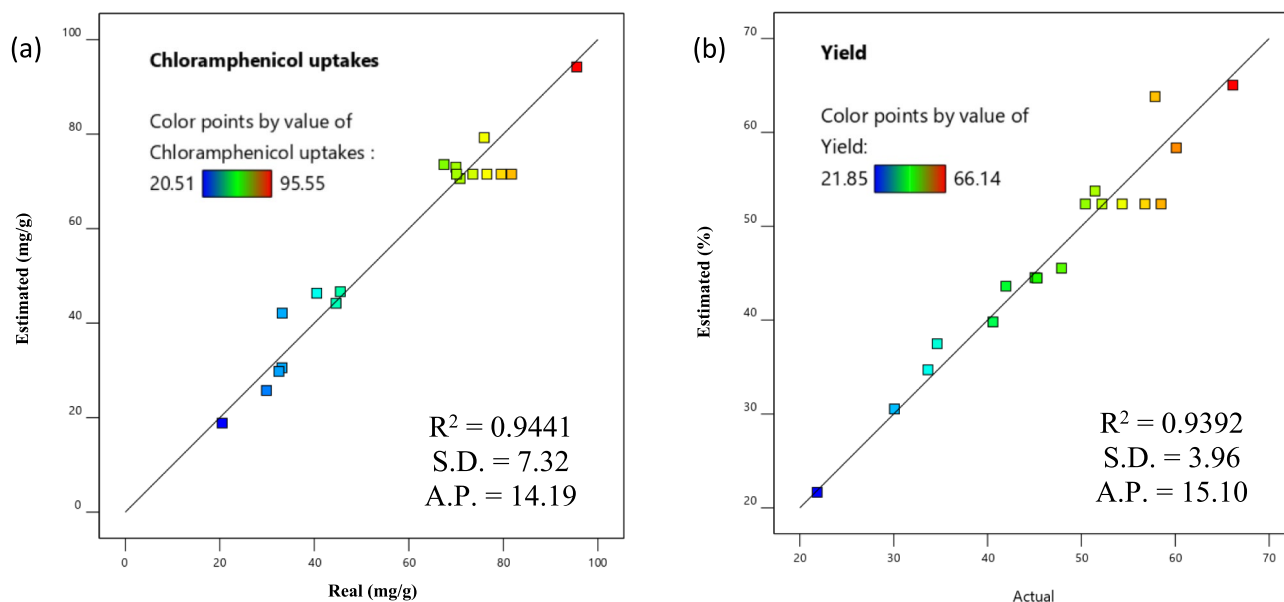


Fig. 2 Regression plots comparing estimated versus real values for **a** Cp uptake and **b** Cu-MFCLT yield



and actual measured values. These high R^2 values suggest that the regression models accurately represent the dataset, effectively capturing a large proportion of the variance in the response variables. Additionally, the standard deviations (S.D.) for Cp uptake and Cu-MFCLT yield were calculated to be 7.32 and 3.92, respectively. Given their respective mean values of 57.61 mg/g for Cp uptake and 47.19% for Cu-MFCLT yield, these S.D. are relatively low, demonstrating consistency and reliability in the data. This consistency is further reinforced by the adequate precision (A.P.) values, which were 14.19 for Cp uptake and 15.10 for Cu-MFCLT yield. Since both values exceed the threshold of 4, they confirm a favourable signal-to-noise ratio, signifying that the models are robust and effective for predictive purposes (Firdaus et al. 2023). This alignment between observed and predicted values supports the model's suitability in accurately explaining the responses of Cp uptake and Cu-MFCLT yield.

Analysis of variance (ANOVA)

Table 2 displays the statistical values of ANOVA for Cp uptake response and Cu-MFCLT yield response. These responses show statistical significance, as evidenced by p-values of 0.0001 for Cp uptake response and 0.0002 for Cu-MFCLT yield response. For Cp uptake, the terms regarded as significant were X_1 , X_2 , X_3 , X_1X_3 , X_1^2 , and X_3^2 . Regarding Cu-MFCLT yield, terms considered significant included X_1 , X_2 , X_3 , and X_1^2 . According to F-values, Cp uptake was most influenced by radiation power (44.41) and MLR (34.56), while Cu-MFCLT yield was primarily affected by MLR (59.58) and radiation power (42.25). Adequate precision (A.P.), a parameter that evaluates the quality of signal-to-noise ratio, was 14.19 for Cp uptake and 15.10 for Cu-MFCLT yield, indicating strong signal reliability for both responses. Ratios surpassing 4 underscore the relevance of the quadratic model, confirming its effectiveness for investigating the design framework (Beyan et al. 2021).

Three-dimensional (3D) responses plot

Figure 3a presents a 3D contour plot illustrating Cp uptake, emphasizing the effects of radiation power and MLR. Conversely, Fig. 3b features a 3D surface plot of Cu-MFCLT yield, illustrating the impact of radiation power and radiation time. As shown in Fig. 3a, the highest Cp uptake, reaching 95.55 mg/g, was obtained under the maximum radiation power of 660 W and the minimum MLR of 0.10 g/g. As the radiation intensity rose from 264 to 660 W, Cp uptake showed a marked rise, especially within the lower MLR range of 0.10–0.40 g/g. This trend underscores the synergistic interaction between radiation power and MLR. The higher radiation power intensified heating, promoting the dissipation of volatile substances from the sample, which, subsequently, generated additional pores and enhanced the surface area (Wan Mahari et al. 2016; Mohamad et al. 2023).

The lower MLR range of 0.10 g/g to 0.40 g/g proved to be the most effective for Cp removal. Within this range, the amount of Cu^{2+} attached to the surface of Cu-MFCLT was optimally sufficient for adsorption. When the MLR exceeded this range, the excess Cu^{2+} began to accumulate, blocking pores on the Cu-MFCLT surface and thereby lowering the number of active adsorption sites. Figure 3b shows that the minimum Cu-MFCLT yield, reaching 21.85%, was observed at the highest radiation power of 660 W and a radiation time of 20 min, highlighting the negative influence of these conditions on yield. As radiation time increased from 12 to 20 min, the decrease in Cu-MFCLT yield became more noticeable, particularly within the 462–660 W radiation power range. The thermal cracking process was markedly enhanced by the combined effect of increased radiation power and extended duration, resulting in a greater loss of sample constituents and ultimately lowering the yield (Firdaus et al. 2025b).

Table 2 ANOVA results for Cp uptake and Cu-MFCLT yield responses

Source	Response 1, Y_1 : Cp uptakes by Cu-MFCLT					Response 2, Y_2 : Cu-MFCLT yield				
	Sum of squares	DF	Mean square	F value	p value	Sum of squares	DF	Mean square	F value	p value
Model	8145.44	9	905.05	16.87	0.0001	2178.91	9	242.10	15.44	0.0002
X_1	2381.77	1	2381.77	44.41	<0.0001	662.27	1	662.27	42.25	0.0001
X_2	746.50	1	746.50	13.92	0.0047	151.24	1	151.24	9.65	0.0126
X_3	1853.68	1	1853.68	34.56	0.0002	933.93	1	933.93	59.58	<0.0001
X_1X_2	13.36	1	13.36	0.2492	0.6296	0.4513	1	0.4513	0.0288	0.8690
X_1X_3	548.80	1	548.80	10.23	0.0109	15.18	1	15.18	0.9684	0.3508
X_2X_3	28.35	1	28.35	0.5286	0.4857	4.96	1	4.96	0.3165	0.5875
X_1^2	533.16	1	533.16	9.94	0.0117	124.74	1	124.74	7.96	0.0200
X_2^2	2.23	1	2.23	0.0416	0.8429	64.85	1	64.85	4.14	0.0725
X_3^2	365.69	1	365.69	6.82	0.0282	8.59	1	8.59	0.5481	0.4780



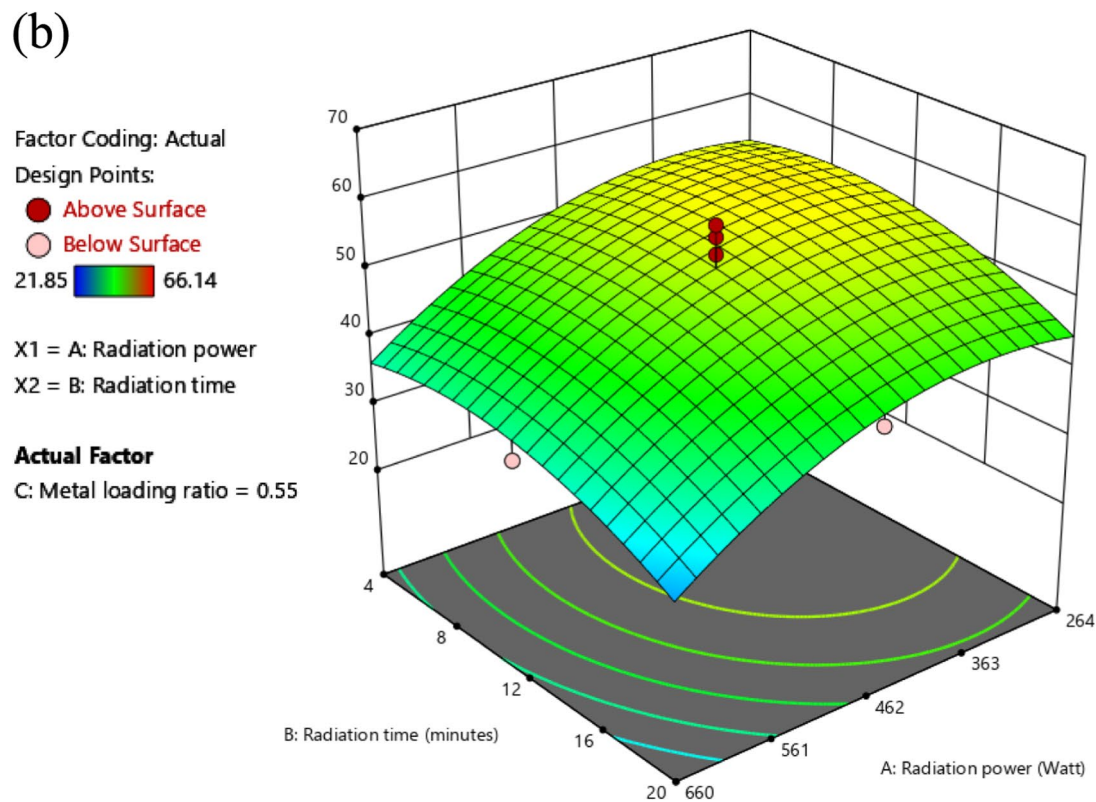
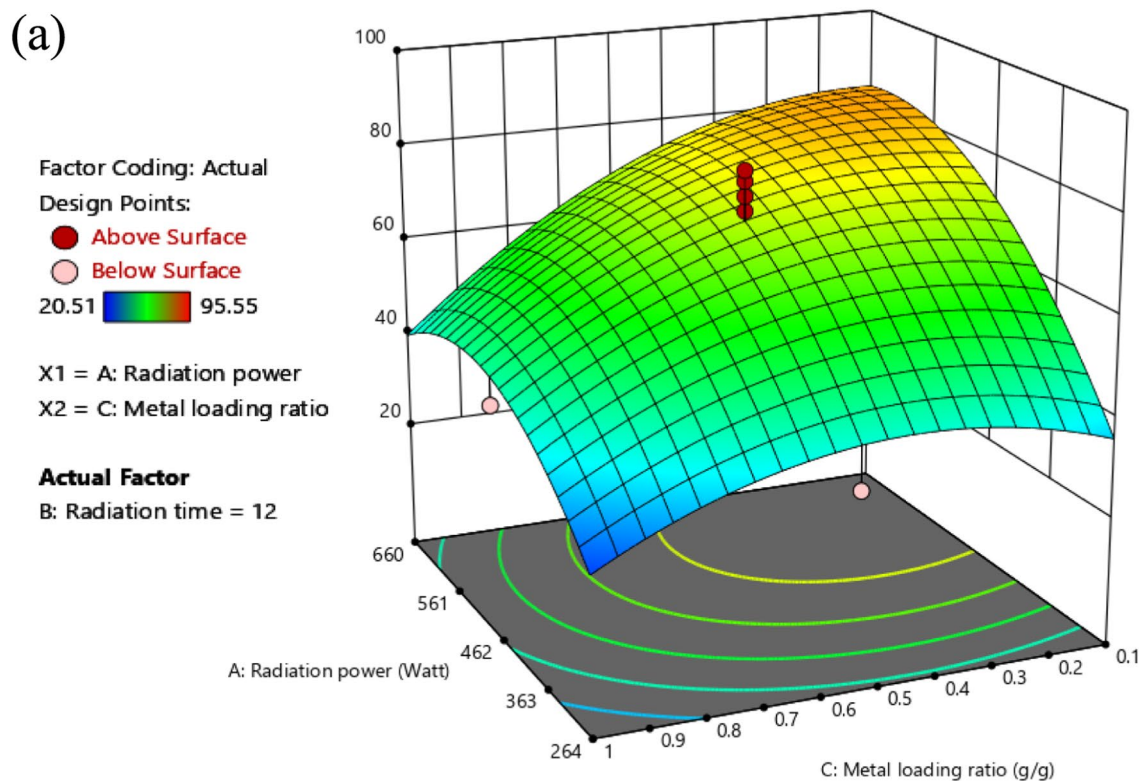


Fig. 3 3D surface plots for **a** Cp uptakes and **b** Cu-MFCLT yield



Optimization verification

The optimal parameters for the variables and responses were determined by minimizing the values of the input variables while maximizing the desired responses. The optimized conditions corresponded to a radiation power of 466.24 W, radiation time of 13.00 min, and MLR of 0.60 g/g. Under these conditions, the predicted Cp uptake and Cu-MFCLT yield were 71.19 mg/g and 52.75%, respectively. The predicted uptake of Cp (71.19 mg/g) and the yield of Cu-MFCLT (52.75%) closely matched the observed experimental results, which were 73.66 mg/g and 51.11%, respectively. The minor errors, calculated at 3.35% for Cp uptake and 3.21% for Cu-MFCLT yield, demonstrate the high accuracy and reliability of the predictive models developed in this study. These low error rates highlight the robustness of the optimization approach used.

Samples characteristic

Elemental and proximate analysis

The elemental analysis revealed that the precursor contained 42.72% C, 5.06% H, 0.75% N, 0.23% S, and 51.24% O. After surface modification with $\text{Cu}(\text{NO}_3)_2$, the elemental content of C, H, N, and S in pristine MFCLT decreased from 76.53%, 3.69%, 0.63%, and 0.11%, respectively, to 74.19%, 3.54%, 0.60%, and 0.10% in Cu-MFCLT. This reduction is attributed to the incorporation of Cu^{2+} onto the surface. Additionally, the increase in other elements from 19.04% in pristine MFCLT to 21.57% in Cu-MFCLT further supports the presence of copper modification.

The proximate analysis indicates that the pyrolysis step and activation methods used in this research successfully reduced moisture and volatile matter, lowering these values from 4.64% and 64.96% in the precursor to 1.99% and 22.09% in pristine MFCLT, respectively (Yusop et al. 2023). As a result, the fixed carbon content significantly improved from 28.96% in the precursor to 74.46% in pristine MFCLT, while the ash content of the precursor and pristine MFCLT remained low at 1.44% and 1.46%, respectively. Upon surface modification with $\text{Cu}(\text{NO}_3)_2$, the Cu-MFCLT did not show substantial changes in its composition, where the moisture, volatile matter, and fixed carbon contents were 2.01%, 22.16%, and 73.65%, respectively, while the increase in the ash content was relatively high, rising from 1.46 to 2.18%. This rise in ash content can be ascribed to the incorporation of Cu^{2+} ions, which contribute to the residual inorganic matter after the combustion process, thereby increasing the overall ash content of the modified material. Nonetheless, according to Firdaus et al. (2025c), a low ash content in the adsorbent (< 5%) enhances adsorption efficiency, as ash is

non-porous and may obstruct active sites when present in excess.

Surface area and pores parameters

The surface area and pore properties of the samples are summarized as follows. Initially, the precursor displayed a low BET surface area (BET-SA) of $2.01 \text{ m}^2/\text{g}$ and a total pore volume (TPV) of $1.0 \times 10^{-4} \text{ cm}^3/\text{g}$. No measurable mesoporous surface area (MESO-SA) or average pore diameter (APD) was detected for the precursor. During carbonization and activation, the removal of moisture and volatile components like cellulose and hemicellulose led to initial pore formation. As the temperature increased during physical activation, the dissipation of heavier volatiles, ranging from hemicellulose to lignin, intensified pore development further. The introduction of CO_2 gas during activation also contributed to the enlargement and increase in the number of pores. Accordingly, pristine MFCLT demonstrated a significantly elevated BET-SA of $875.65 \text{ m}^2/\text{g}$ and a MESO-SA of $634.12 \text{ m}^2/\text{g}$. Its TPV reached $0.3886 \text{ cm}^3/\text{g}$, with an APD of 2.98 nm, indicating a well-developed mesoporous structure. After modification with $\text{Cu}(\text{NO}_3)_2$, the BET-SA, MESO-SA, TPV, and APD slightly decreased to $866.86 \text{ m}^2/\text{g}$, $627.17 \text{ m}^2/\text{g}$, $0.3871 \text{ cm}^3/\text{g}$, and 2.93 nm, respectively. This minor decrease was expected due to the partial coverage of the MFCLT surface by Cu^{2+} ions. The APD of 2.93 nm falls well within the mesoporous range of 2–50 nm, which has been shown to be beneficial for molecular adsorption owing to enhanced pore accessibility and mass transport in carbon materials (Wei et al. 2025).

SEM images

The SEM images in Fig. 4 provide a comparative analysis of the surface morphology between the precursor and Cu-MFCLT samples. In Fig. 4a, the SEM image of the precursor reveals a relatively smooth, dense surface with no visible pores. This suggests a lack of significant porosity, typical of untreated biomass materials, due to the presence of moisture, fibrous polysaccharides, hemicellulose compounds, and lignified structures, which occupy the internal matrix. In contrast, Fig. 4b shows the SEM image of Cu-MFCLT. The surface morphology is significantly altered, displaying a highly porous structure with well-developed, interconnected pores. This transformation is a result of the carbonization and activation processes, where the thermal decomposition of cellulose and hemicellulose leads to the creation of initial pores. The physical activation with CO_2 gas further enhances pore development by etching the carbon surface, removing volatile components, and creating additional vacant sites. The manifestation of Cu^{2+} ions on the surface of Cu-MFCLT does not obscure the pore structure, indicating successful



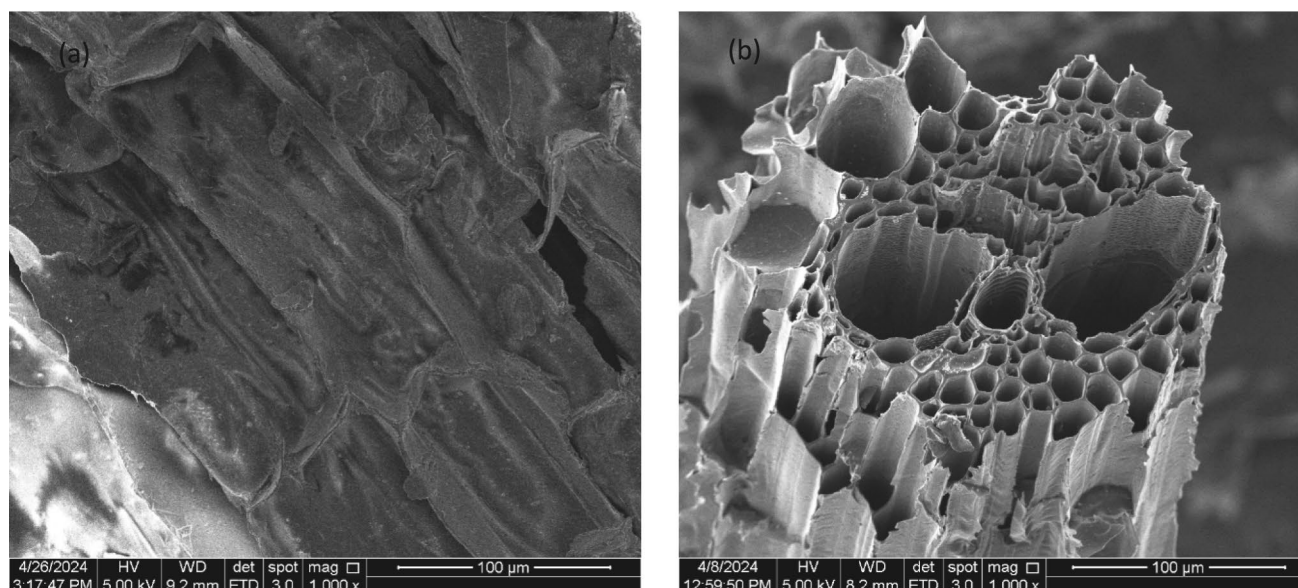


Fig. 4 SEM images for **a** precursor and **b** Cu-MFCLT (magnification level of 1000 $\times$)

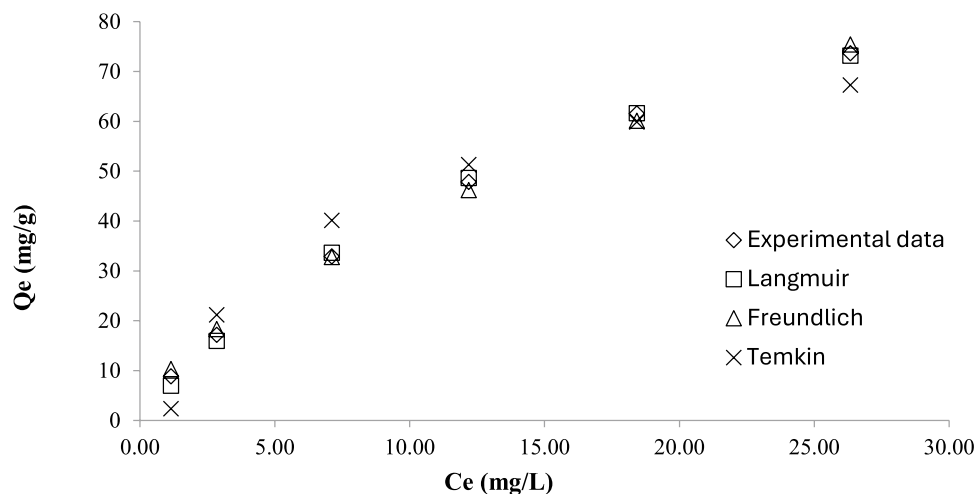
modification without blocking the pores. The interconnected mesopores and visible porosity in Cu-MFCLT contribute to a larger surface area, which provides a beneficial attribute for adsorption-related applications.

Adsorption isotherm

Figure 5 displays the isotherm model plots. Considering the RMSE values, the Langmuir model exhibited the most accurate fit for the Cp-Cu-MFCLT adsorption system, showing the lowest RMSE of 1.04 mg/g, while Freundlich and Temkin produced higher RMSE values of 1.38 mg/g and 5.27 mg/g, respectively. The Langmuir model implies that Cp adsorption onto the Cu-MFCLT surface occurs via monolayer formation, with a K_L of 0.049 L/mg. The

adsorption performance of Cp onto Cu-MFCLT is attributed to the presence of copper species, which introduce additional active sites that strengthen adsorbate–adsorbent interactions. Specifically, copper sites facilitate ion–dipole interactions with polar functional groups of Cp, including the hydroxyl (–OH), amide carbonyl (–C=O), and nitro (–NO₂) groups (Firdaus et al. 2025a; Mohamad et al. 2024). In addition, coordination interactions between copper ions and Cp predominantly involve the amide carbonyl oxygen and the hydroxyl oxygen atoms of the propanediol moiety, with minor contributions from nitro group oxygens, thereby reinforcing adsorption beyond physical pore filling (Mohamad et al. 2025). The Freundlich parameters of K_F and n_F were found to be 9.41 (mg/g)(L/mg)^{1/ n_F} and 1.57, respectively. Since n_F was between 1 and 10, this suggests a

Fig. 5 Isotherm graphs for Cp-Cu-MFCLT adsorption system at 30 °C



favourable adsorption process. The Q_m reached 129.58 mg/g, which is notably higher compared to Cp removal using sodium bicarbonate-impregnated coconut husk-based AC of 4.94 mg/g (Anthonysamy et al. 2023), CO_2 -activated paper sewage sludge-based AC of 17.08 mg/g (Aziz et al. 2023), CO_2 -activated palm kernel shell-based AC of 18.95 mg/g (Luqman et al. 2025) and CO_2 -activated rambutan peel-based AC of 33.08 mg/g (Aziz et al. 2024). The substantial improvement in Cp adsorption performance demonstrated by Cu-MFCLT indicates that surface modification using $\text{Cu}(\text{NO}_3)_2$ is considerably more effective than physical activation or non-metal chemical treatment alone. The performance of Cu-MFCLT for Cp removal is superior when compared with other metal-functionalized activated carbons, such as Cu-functionalized carbon derived from rattan waste with an adsorption capacity of 108.00 mg/g (Mohamad et al. 2025), as well as manganese dioxide-functionalized rice husk biochar used for the removal of tetracycline and doxycycline antibiotics, which exhibited adsorption capacities of 25.50 mg/g and 25.50–31.34 mg/g, respectively (Li et al. 2020). Despite the lower suitability of the Temkin model for this adsorption system, the Temkin parameters A_T and B_T were found to be 0.97 L/mg and 20.73 J/mol, respectively.

Adsorption kinetic and diffusion mechanism

Figure 6a and b describe the kinetic plots for the PFO and PSO models, respectively, while Fig. 6c shows the Boyd plot. The parameters for the PFO and PSO models are provided in Table 3. The PFO kinetic model displayed the most suitable match for the Cp adsorption onto Cu-MFCLT, as indicated by the lowest RMSE of 1.27 and the smallest error of 8.59%. This model implies that the adsorption process is primarily ruled by diffusion steps. The rate constant, k_1 , reduced from 0.77 to 0.39 h^{-1} as the Cp concentration escalated from 10 to 100 mg/L. At higher concentrations, the decline in k_1 indicates a reduction in the diffusion rate, likely due to intensified rivalry among Cp molecules for available adsorption sites, resulting in a slower adsorption process. The PFO model has also been effective in describing the adsorption of other antibiotics, such as diclofenac using covalent organic frameworks (Zhuang et al. 2020) and minocycline adsorption by magnetic ordered carbon (Hu et al. 2019). Figure 6c was constructed to identify the rate-limiting diffusion step in the Cp adsorption process onto Cu-MFCLT. The plots failed to intersect the origin for any of the initial Cp concentrations, signifying that the adsorption process is regulated by film diffusion.

Adsorbent regeneration

Figure 7 illustrates the regeneration behavior of Cu-MFCLT using two distinct regeneration methods: (a) thermal

regeneration and (b) solvent regeneration. As shown in Fig. 7a, both Cp removal efficiency and Cu-MFCLT yield declined progressively with increasing regeneration cycles. While the fresh adsorbent exhibited 100% removal efficiency and yield, these values decreased to 87.96% and 76.51%, respectively, after the first cycle and further deteriorated to 10.85% removal efficiency and 4.45% yield by Cycle 5. Although microwave-assisted thermal regeneration was initially effective, its ability to restore adsorption capacity diminished rapidly upon repeated application. This behavior is attributed to structural degradation of Cu-MFCLT induced by repeated thermal exposure, which likely caused pore collapse, surface smoothing, and loss of active adsorption sites. Similar observations have been reported in previous studies, where adsorption saturation and thermal stress led to pore blockage and reduced surface roughness, thereby limiting regeneration efficiency (Hu et al. 2025). Consistent with this trend, thermal regeneration has been reported to significantly reduce both adsorption performance and adsorbent yield, as evidenced by the decrease in amoxicillin removal by orange peel-based activated carbon to 32.38% and the corresponding yield to 52.63% after three regeneration cycles (Firdaus et al. 2025a).

In contrast, as shown in Fig. 7b, solvent regeneration using ethanol consistently produced higher Cp removal efficiency and Cu-MFCLT yield. In the first regeneration cycle, Cp removal and Cu-MFCLT yield reached 91.52% and 93.62%, respectively. Even after five regeneration cycles, the Cp removal efficiency and Cu-MFCLT yield remained relatively high at 65.82% and 73.52%, respectively, demonstrating the superior performance of solvent regeneration compared to thermal regeneration. Cp exhibits moderate hydrophobicity ($\log K_{ow} \approx 1.1\text{--}1.2$), whereas ethanol is a hydrophilic solvent ($\log K_{ow} \approx -0.3$), enabling ethanol to solvate Cp and weaken adsorbent–adsorbate interactions with only limited competition for adsorption sites. In addition, solvent regeneration is less aggressive than thermal treatment and is therefore expected to minimize pore damage and mass loss. This preservation is consistent with the observation that Cu-MFCLT yield consistently remained higher than Cp removal efficiency across all five solvent regeneration cycles, whereas the opposite trend was observed for thermal regeneration. These results confirm the higher stability and regeneration efficiency of the solvent regeneration method.

Synthesis cost evaluation of Cu-MFCLT production

A synthesis cost evaluation was conducted to assess the economic feasibility of Cu-MFCLT under laboratory-scale conditions. The total cost was divided into the following components:



Fig. 6 The plots for **a** PFO, **b** PSO and **c** Boyd plot for Cp-Cu-MFCLT adsorption system at 30 °C

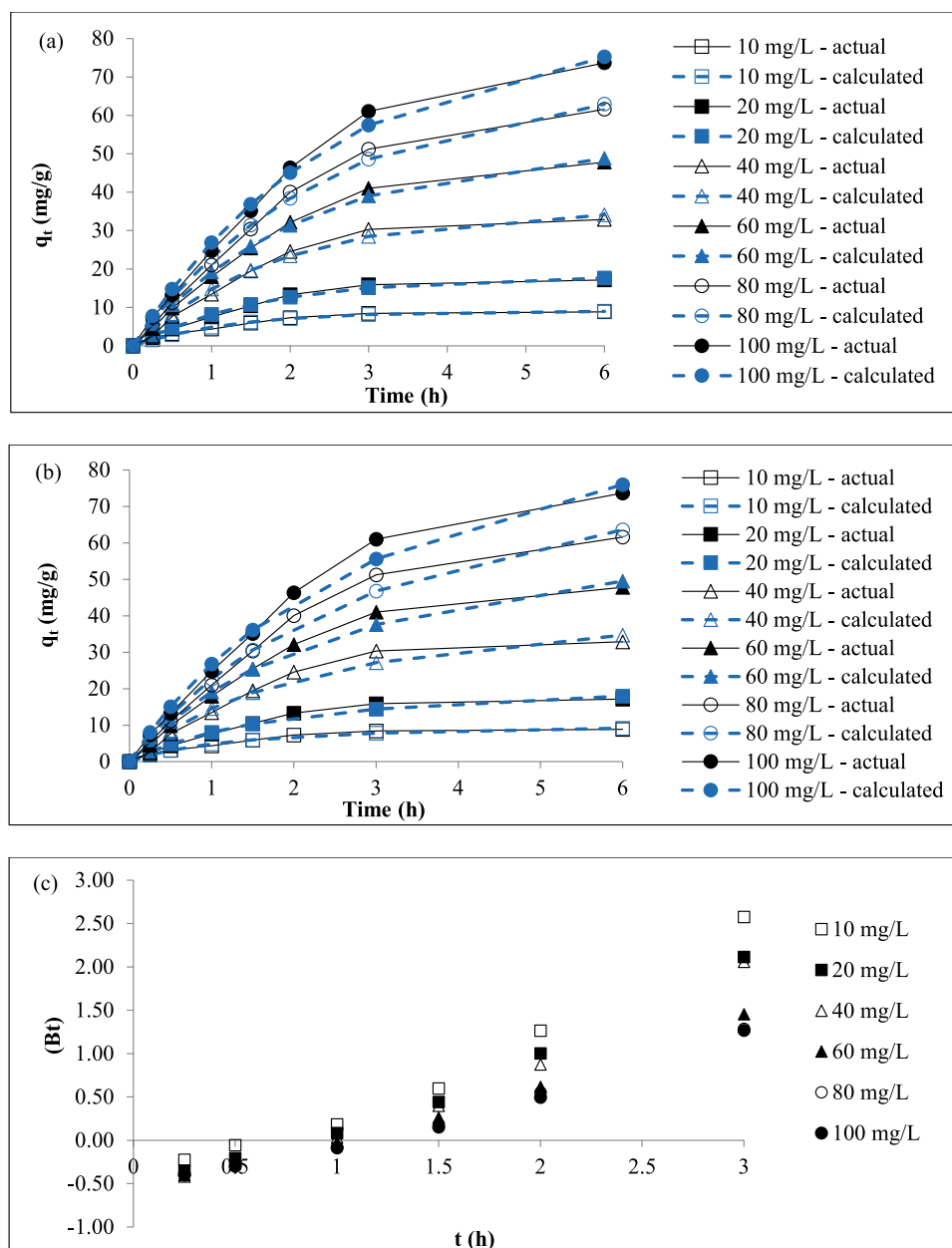


Table 3 Kinetic parameters for Cp-Cu-MFCLT adsorption system at 30 °C

Cp initial concentration (mg/L)	q_e , exp. (mg/g)	PFO				PSO			
		q_e , cal. (mg/g)	k_1 (h^{-1})	Error (%)	RMSE	q_e , cal. (mg/g)	k_2 (g/mg.h)	Error (%)	RMSE
10	8.85	9.07	0.77	8.22	1.27	11.14	0.069	7.23	1.63
20	17.15	18.19	0.60	5.41		23.89	0.021	9.05	
40	32.89	35.52	0.54	15.75		48.07	0.009	21.92	
60	47.81	52.15	0.46	7.34		72.49	0.005	14.72	
80	61.58	68.95	0.41	8.99		99.35	0.003	15.55	
100	73.66	83.21	0.39	5.82		120.17	0.002	13.09	
Average	—	—	—	8.59	—	—	—	13.59	—

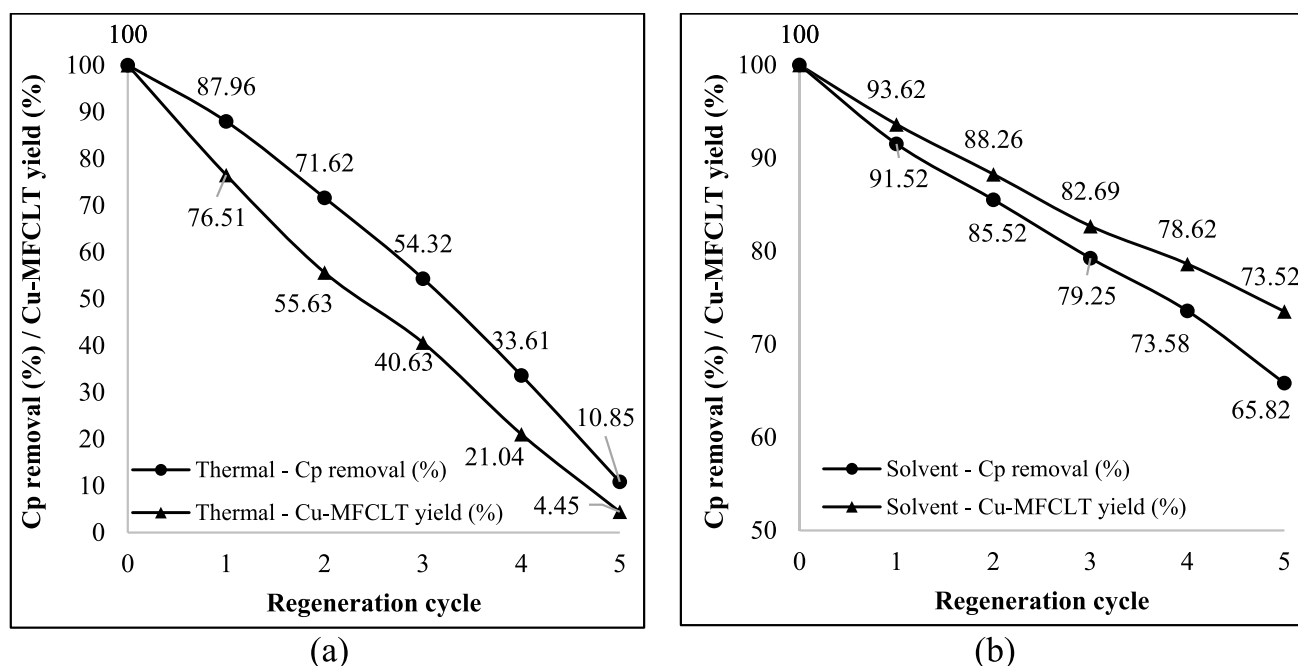


Fig. 7 Regeneration plots for Cp-Cu-MFCLT adsorption system via **a** thermal method and **b** solvent method

- (i) The raw precursor consisted of 50 g of *Lansium parasiticum* trunk waste, which was obtained at no cost, resulting in zero raw material expenditure.
- (ii) Carbonization under N_2 at a flow rate of $150 \text{ cm}^3/\text{min}$ contributed an estimated gas cost of USD 4.77 per batch, while the corresponding furnace electricity consumption using a 2 kW furnace accounted for approximately USD 0.18.
- (iii) Microwave activation required minimal electrical energy, with an estimated cost of USD 0.006 per batch. The associated CO_2 gas consumption at a flow rate of $150 \text{ cm}^3/\text{min}$ contributed an estimated cost of USD 1.03.
- (iv) Surface modification was performed using $Cu(NO_3)_2$ at a MLR of 0.60 g/g, corresponding to approximately 30 g of $Cu(NO_3)_2$ per batch. This resulted in a cost of approximately USD 0.90 per batch.

By summing all cost components, the total synthesis cost of Cu-MFCLT was estimated to be USD 6.89 per batch using 50 g of precursor. Considering a product yield of 51.11%, equivalent to approximately 25.56 g of final Cu-MFCLT per batch, the preparation cost was calculated to be USD 269.50/kg. Although this value is higher than that of conventional commercial AC, typically reported at USD 2–5/kg, the increased cost is attributable to laboratory-scale production conditions, including higher energy tariffs and non-optimized processing.

Comparable laboratory-scale studies have reported high preparation costs such as USD 451.20/kg for copper-functionalized carbon from rattan waste (Mohamad et al. 2025) and USD 414.00/kg for deprotonated grape stem functionalized carbon (Firdaus et al. 2025c). Moreover, the economic viability of Cu-MFCLT is further supported by its regeneration capability, maintaining Cp removal efficiency of 54.32% and Cu-MFCLT yield of 40.63% after three regeneration cycles. These findings indicate that, despite higher unit preparation costs at laboratory scale, Cu-MFCLT demonstrates favourable cost-to-performance characteristics for wastewater treatment applications.

Conclusion

The Cu-MFCLT was effectively synthesized under optimal conditions identified through RSM: 466.24 W, an activation time of 13 min, and a MLR of 0.60 g/g. Under these conditions, Cu-MFCLT achieved a Cp uptake of 71.19 mg/g and a yield of 52.75%. The predictive model established great accuracy, with minimal errors of 3.35% and 3.21%, respectively. The optimized Cu-MFCLT exhibited a BET-SA of $866.86 \text{ m}^2/\text{g}$, a MESO-SA of $627.17 \text{ m}^2/\text{g}$, a TPV of $0.3871 \text{ cm}^3/\text{g}$, and an APD of 2.93 nm. Isotherm analysis showed that the adsorption system was best described by the Langmuir model, indicating monolayer adsorption of Cp molecules onto the Cu-MFCLT surface, with a



Q_m of 129.58 mg/g. Kinetic assessment revealed that the adsorption process complied with the PFO model, with k_1 values ranging from 0.77 to 0.39 h⁻¹ as the C_p concentration increased from 10 to 100 mg/L. Regeneration studies showed that ethanol solvent regeneration was more effective than microwave-assisted thermal regeneration, maintaining C_p removal above 65% and Cu-MFCLT yield above 70% after five cycles. In contrast, thermal regeneration caused rapid deterioration in adsorption performance and material yield. Thus, ethanol regeneration is identified as the optimal strategy for ensuring stable reusability and economic feasibility.

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Declarations

Conflict of interest The authors declare that they have no competing interest.

Human and animal participants This article does not contain any studies with human participants performed by any of the authors.

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