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Research Article

Coffee Waste as a Potential Adsorbent for Peat Water Treatment

Ampas Kopi Sebagai Adsorben yang Berpotensi untuk Pengolahan Air Gambut

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Abstract

Peat water is characterized by high acidity, turbidity, and poor sensory qualities, which limit its usability. This study evaluated the effectiveness of thermally activated coffee waste adsorbent (CWA) for peat water treatment. CWA was prepared by heating coffee waste at 250°C, followed by washing and drying at 60°C. Batch adsorption experiments were conducted using 1–3 g of CWA in 200 mL of peat water at 30°C, stirred at 150 rpm for 30 minutes. The results revealed significant improvements in water quality: pH increased from 3.85 to 4.62; turbidity was reduced by 99.37% (from 75 to 0.47 NTU); conductivity decreased by 30.7% (from 424 to 294 µS/cm); and total dissolved solids (TDS) dropped by 93.3% (from 208 to 14 ppm). The Langmuir isotherm model (R^2 = 0.7297) provided a better fit than the Freundlich model (R^2 = 0.5845), indicating monolayer adsorption behavior with a maximum capacity of 0.1634 mg/g and a favorable separation factor (*RL* = 0.0057). Sensory evaluation confirmed enhanced color and odor. These findings support the use of CWA as a sustainable and low-cost adsorbent for improving peat water quality.

Keywords: adsorbent; adsorption isotherm; coffee waste; peat water treatment

Abstrak

Air gambut memiliki keasaman dan kekeruhan yang tinggi, dan kualitas sensorik yang buruk, sehingga membatasi kegunaannya. Penelitian ini mengevaluasi efektivitas adsorben limbah kopi (CWA) yang diaktivasi secara termal untuk pengolahan air gambut. CWA disiapkan melalui pemanasan pada suhu 250°C, kemudian dicuci dan dikeringkan pada suhu 60°C. Eksperimen adsorpsi secara batch dilakukan dengan menggunakan 1–3 g CWA dalam 200 mL air gambut pada suhu 30°C, diaduk pada kecepatan 150 rpm selama 30 menit. Hasil penelitian menunjukkan peningkatan kualitas air, berupa peningkatan nilai pH dari 3,85 menjadi 4,62; nilai kekeruhan berkurang sebesar 99,37% (75 menjadi 0,47 NTU); konduktivitas menurun sebesar 30,7% (424 menjadi 294 µS/cm); dan TDS turun sebesar 93,3% (208 menjadi 14 ppm). Model isoterm Langmuir (R^2 = 0,7297) lebih sesuai dibandingkan model Freundlich (R^2 = 0,5845), hal ini menunjukkan bahwa adsorpsi terjadi secara monolayer dengan kapasitas maksimum 0,1634 mg/g dan faktor pemisahan yang lebih baik (RL = 0,0057). Evaluasi sensorik mengkonfirmasi peningkatan warna dan bau. Penelitian ini mendukung bahwa CWA sebagai adsorben berkelanjutan dan berbiaya rendah untuk meningkatkan kualitas air gambut.

***Kata kunci**: adsorben; air gambut; ampas kopi; isoterm Adsorpsi*

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1. Introduction

Access to clean water remains a critical challenge in Jambi Province, Indonesia, primarily due to the prevalence of peat water, which is often characterized by high levels of organic matter, iron, and manganese [1]. According to data from the Indonesian Ministry of Health, only 67.5% of households in Jambi Province had access to clean water sources as of 2021, a figure lower than the national average of 73.7%, underscoring the region's urgent need for improved water treatment solutions [2].

Peat water in Jambi exhibits elevated levels of dissolved organic matter, resulting in a blackish-brown coloration, high total dissolved solids (TDS), and low pH. Consequently, its treatment has become a central focus of environmental management and public health initiatives [3]. Various strategies have been implemented to improve water quality; however, the treatment of peat water remains a complex challenge. Several methods have been employed, including adsorption, filtration, oxidation, and coagulation, each with varying degrees of success and context-specific applicability [1].

Among these, adsorption has emerged as one of the most promising methods due to its operational simplicity, cost-effectiveness, and high removal efficiency for organic compounds [4]. Numerous adsorbents have been investigated for their ability to reduce TDS, turbidity, and color in peat water. A composite adsorbent comprising *Pahae* natural zeolite and activated carbon effectively reduced color from 175.4 TCU to 41.7 TCU (a 76.2% reduction), decreased turbidity from 31.32 NTU to 11.24 NTU (a 64.1% reduction), and adjusted pH from 5.0 to a more neutral 6.8 [5]. Similarly, magnetic chitosan composite beads have demonstrated promise in reducing organic matter and color, highlighting their dual function in enhancing the appearance and quality of treated peat water [6]. Activated carbon derived from robusta coffee pulp waste has proven effective in lowering iron levels in peat water from 2.75 mg/L to 0.95–1.19 mg/L. Synthetic zeolite has also been studied for its effectiveness in removing organic constituents while reducing color and TDS. The porous network of zeolite facilitates the entrapment of dissolved organic molecules [7].

Being readily available and often discarded without further use, coffee waste presents an innovative solution to waste management and water quality issues in the region. Previous studies have demonstrated that coffee waste possesses adsorption capabilities that effectively reduce contaminants and organic matter from water [8]–[11]. Recent research has increasingly shown that coffee waste, including husks and spent coffee grounds, can be converted into efficient adsorbents for removing organic matter, particularly organic dyes, offering a sustainable approach to wastewater remediation. Simple physical washing of spent coffee grounds was found to be sufficient to enhance their adsorption capacity for organic dyes such as methylene blue [12]. Similarly, coffee waste has proven effective in removing toluidine blue and crystal violet dyes from water, achieving high adsorption capacities of 142.5 mg/g and 125 mg/g, respectively [13].

The adsorption performance of coffee waste is attributed to its chemical composition, which includes carboxyl and hydroxyl groups (–COOH, –OH) derived from polysaccharides such as cellulose and hemicellulose, as well as the polymeric compound lignin [12]. These functional

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groups provide multiple binding sites, significantly enhancing the material's adsorption capabilities for various organic pollutants. Several factors affect adsorption behavior, including the structure and size of organic molecules, the surface properties of the adsorbent, steric effects, hydrogen bonding, and van der Waals forces. For instance, interactions between dye molecules and coffee waste occur through bonding between nitrogen-containing amine groups in the dye and the surface of the coffee waste, as well as electrostatic interactions between cationic dye molecules (N^+) and the negatively charged surface of coffee waste under basic conditions [13].

The primary objective of this study was to investigate the efficacy of spent coffee ground waste as an adsorbent for peat water purification, with a focus on reducing TDS, turbidity, and color using a simple activation process. While previous studies have predominantly explored the use of coffee waste adsorbents (CWA) for removing pollutants such as heavy metals and dyes from conventional wastewater [8], [13]–[15], the present research emphasized its application in peat water treatment. This approach minimizes the complexity of the treatment process, making it accessible to individuals and communities with limited resources. Given the unique challenges of peat water, especially its high organic content, the adsorption capability of CWA offers a promising solution. As a readily available byproduct of the coffee industry and coffee shops, coffee waste presents a dual opportunity to support sustainable waste management and water quality improvement. This study also evaluated various experimental parameters, including water color, pH, conductivity, turbidity, and TDS, in relation to adsorption performance.

2. Research Methods

2.1 Materials

Ground coffee waste was collected from a local coffee brand in Jambi City, specifically using Robusta coffee from the commercial brand *Kopi Bubuk Cap AAA*. The coffee waste used as the adsorbent was prepared using a simple method. CWA was produced by heating the material at 250°C for 30 minutes in an oven. Afterward, it was washed several times with distilled water to remove any adhering dirt and color until the rinsing water remained clear, and then it was dried at 60°C for 30 minutes in the oven. This study aimed to assess the performance of coffee waste as an adsorbent to purify the peat water, which appeared blackish-brown and had an acidic pH of 3.85, collected from peatlands in Jambi City.

2.2 Adsorption Experiment

The adsorption experiment used the prepared coffee waste as the adsorbent and the contaminants present in the peat water as adsorbates. The experiments were conducted in 500 mL glass flasks, each containing 200 mL of peat water and 1, 2, or 3 g of CWA. A magnetic stirrer was used to agitate the mixture at 150 rpm for 30 minutes. The adsorption temperature was maintained at 30 ± 2°C. After the process, the treated water was filtered to obtain the samples for analysis. The parameters analyzed before and after the experiment included temperature, TDS using a digital TDS & EC meter (range up to 9990 ppm/µS/cm, manufactured in China), turbidity using a Lutron TU-2016 turbidimeter (measurement capability up to 1000 NTU, Taiwan), pH using an APLUSTE digital pH meter (China), and conductivity using a digital conductivity meter (range up to 9990 µS/cm, China).

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Color and odor were also evaluated using a human-sensory approach. A 1–5 visual scale was applied for color assessment, where 1 indicated very cloudy and blackish-brown water, and 5 indicated clear and transparent water.

The adsorption capacity and removal efficiency of the coffee waste were calculated to evaluate the effectiveness of the adsorbent in reducing contaminants, particularly TDS. The adsorption capacity was calculated using equation (1), where *Co* (mg/mL) and *Ce* (mg/mL) were the initial and final TDS concentrations, *V* was the volume of peat water (mL), and *m* was the mass of the adsorbent (g) [13]. The removal efficiency was calculated using equation (2).

$$qe = \frac{(Co - Ce)\,V}{m} \quad \text{.....(1)}$$

$$Removal\ eff.(\%) = \frac{Co-Ce}{Co} \times 100\ \% \quad \text{..(2)}$$

2.3 Adsorption Isotherm

Adsorption isotherms are essential for understanding the adsorption capacity of adsorbents and the interactions between adsorbents and adsorbates. The Langmuir and the Freundlich models are the most commonly applied. The Langmuir model assumes monolayer adsorption on a homogeneous surface, while the Freundlich model applies to both physical and chemical adsorption processes and does not assume lateral interactions among adsorbed molecules [11]. In this study, the linearization method used for the Langmuir model was Linearization III (Eadie–Hofstee). The series of experimental values were fitted using both the Langmuir and the Freundlich isotherm models, represented by equation (3) and equation (4).

$$qe = qm - \left(\frac{1}{KL}\right) \times \frac{qe}{Ce} \quad \text{.....(3)}$$

$$\log qe = \log KF + \left(\frac{1}{n}\right) \log Ce \quad \text{.....(4)}$$

$$RL = \frac{1}{(1 + KL \times Co)} \quad \text{.....(5)}$$

qe (mg/g) represents adsorption capacity, qm (mg/g) is the maximum adsorption capacity, *KL* (L/mg) is the Langmuir adsorption equilibrium constant, *KF* (L/mg) is the empirical constantity of Freundlich isotherm associated with adsorption capacity, and the constant n is the empirical parameter related to the adsorption intensity of the adsorbent. When 1/n values are in the range of 0.1-0.5, the adsorption process is favorable [13]. By using the Eadie–Hofstee linearization (Linearization III) of the Langmuir equation, the adsorption parameters qm and *KL* can be determined from the slope and intercept of the plotted data, respectively. The Freundlich constants were calculated by using the same method as for Langmuir as a comparison.

The Langmuir isotherm is characterized by the Langmuir separation factor (*RL*) and is expressed by the equation (5). The adsorption tends to favor the adsorption equilibrium were judged by the value of *RL*. The value of *RL*, which was in the range of *RL*>1, implying an unfavorable adsorption; *RL*=1, linear adsorption; 0<*RL*<1, favorable adsorption; *RL*=0, irreversible adsorption [8].

3. Results and Discussion

3.1 Organoleptic Properties on CWA Adsorption

The use of CWA demonstrated a significant visual improvement in the treatment of peat water. Based on human sensory observations of color and odor parameters, the results show that increasing

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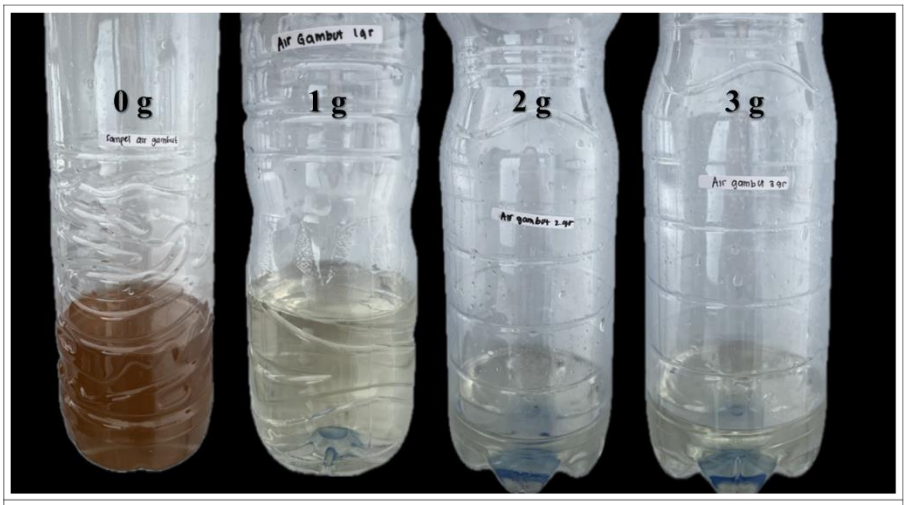
the dosage of CWA led to clearer and more transparent treated peat water, as observed visually. The color evaluation scale is presented in Figure 1, where a 1 g dose of CWA yielded a value of 3, representing a 2-point improvement. Doses of 2 g and 3 g resulted in a value of 4, indicating no significant visual difference between these two treatments. In terms of odor, the initial and final assessments showed considerable improvement. Initially, the water sample exhibited a strong earthy and musty odor. After treatment with CWA, this odor was significantly reduced, leaving only a slight fishy smell in samples treated with 1, 2, and 3 g doses. These findings indicate that CWA could effectively improve odor quality, although complete odor removal might require additional or complementary treatment methods.

The presence of organic matter in peat water, known as natural organic matter (NOM), can be effectively adsorbed by CWA due to its high affinity for such compounds [16],[17]. The complex composition of NOM in peat water, including humic substances, polysaccharides, nitrogen-containing compounds, and volatile organic compounds (VOCs), is primarily responsible for the undesirable odor [18],[19]. The observed reduction in earthy and musty odors following CWA adsorption can be attributed to chemical and physical interactions between the adsorbent and odor-causing compounds. Functional groups such as –OH and –COOH, along with the porous structure of CWA, facilitated the adsorption of NOM via hydrogen bonding, steric effects, and van der Waals forces [13],[20],[21].

The reduction of these elements through adsorption further enhanced the sensory characteristics of the treated peat water, making it less odorous [22]. Previous studies have reported that various low-cost natural adsorbents, such as powdered eggshell [23], chitosan composites [6], and modified red mud [24] have effectively reduced odor-causing compounds through adsorption.



Color evaluation results:			
1	3	4	4
#684A32	#A4A698	#AEB4A8	#AEB5A8

Figure 1. Image of initial and final peat water using coffee waste adsorbent at doses of 0, 1, 2, and 3 g, along with the odor sensory assessment result (Scale 1 to 5)

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3.2 Effect of CWA Dosage

Several parameters were observed to assess the effect of CWA dosage on peat water adsorption. Figure 2(d) shows that the correlation between CWA dosage and pH revealed significant insights into the adsorption process. The data demonstrated a significant positive correlation between CWA dosage and pH values, with the pH increasing from 3.85 to 4.62 as the dosage increased from 0 to 3 g. The pH behavior exhibited interesting characteristics: the initial pH of 3.85 indicated an acidic environment, and although the pH increased, the final value of 4.62 remained within the acidic range. This indicated a limited alkalinity contribution from the CWA. Despite the observable increase, the magnitude of the pH change was relatively modest. This slight shift suggested that the buffering capacity of CWA was moderate, an advantageous property in applications requiring stable pH conditions. The presence of organic compounds in CWA, particularly functional groups such as hydroxyl (-OH) and carboxyl (-COOH), facilitated interactions with protons (H^+) in aqueous solutions. The release of hydroxyl ions (OH^-) by CWA reacted with hydrogen ions (H^+), resulting in the observed pH increase [10],[13],[25]. However, the gradual nature of this change suggested that the adsorption mechanism was not primarily driven by pH variation. Instead, surface area, pore structure, and specific surface interactions might have played more dominant roles in the adsorption process [13].

As shown in Figure 2(a), the study also demonstrated the exceptional effectiveness of CWA in reducing the turbidity of peat water. Turbidity decreased from 75 NTU to 0.47 NTU as the CWA dosage increased from 0 to 3 g, corresponding to a turbidity removal efficiency of approximately 99.37%. The first phase exhibited a sharp decline from 75 NTU to 1.85 NTU when the CWA dosage increased from 0 to 1 g, indicating rapid and efficient removal of suspended particles. From 1 to 3 g, turbidity further decreased gradually from 1.85 NTU to 0.47 NTU. Several mechanisms might explain this high turbidity removal efficiency. CWA likely possessed a well-developed porous structure and high surface area that enhanced the capture of suspended particles [26]. Additionally, coffee waste naturally contains coagulant compounds that support turbidity reduction. For instance, polysaccharides in coffee mucilage have been shown to promote particle aggregation, thereby improving removal rates [27]. The final turbidity value of 0.47 NTU fell well below common water quality standards, indicating that CWA could serve as a promising and sustainable alternative for peat water treatment applications.

The effect of CWA dosage on the conductivity of peat water also revealed a significant reduction pattern that aligned with the turbidity removal trend. Conductivity decreased from 424 µS/cm to 294 µS/cm as the CWA dosage increased from 0 to 3 g, representing a total reduction of approximately 30.7%. In the initial phase, conductivity dropped sharply from 424 µS/cm to 320 µS/cm with a dosage increase from 0 to 1 g, suggesting substantial removal of ionic compounds and dissolved solids. This notable decrease was attributed to the strong interaction between ionic species in the peat water and the active binding sites on the CWA surface. In the second phase, with an increase from 1 to 3 g of CWA, conductivity continued to decrease gradually from 320 µS/cm to 294 µS/cm.

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The effect of CWA dosage on the conductivity of peat water revealed a significant reduction pattern, which was attributed to the unique properties of CWA and its interactions with dissolved ions in the water. The adsorption of cations and anions onto the surface of the CWA particles explained the underlying mechanism of this reduction. Upon introduction into the peat water, CWA interacted with dissolved compounds, effectively binding them to its surface. As the adsorbent mass increased, the available surface area expanded, and the concentration gradient between the bulk solution and the active sites on the CWA intensified, thereby enhancing diffusion. This process significantly reduced the concentrations of dissolved substances and improved the overall water quality by removing various dissolved pollutants [13], [28].

The relationship between CWA dosage and its performance in TDS removal was investigated through the analysis of CWA adsorption capacity (*qe*) and removal efficiency. The TDS removal pattern showed a remarkable improvement with increasing CWA dosage. Initially, the TDS concentration of 208 ppm gradually decreased to 160 ppm and 151 ppm at 1 and 2 g of CWA, respectively, and was then further reduced to 14 ppm at a 3 g CWA dosage. This progression corresponded to removal efficiencies of 23.1%, 27.4%, and 93.3% for 1, 2, and 3 g of CWA, respectively.

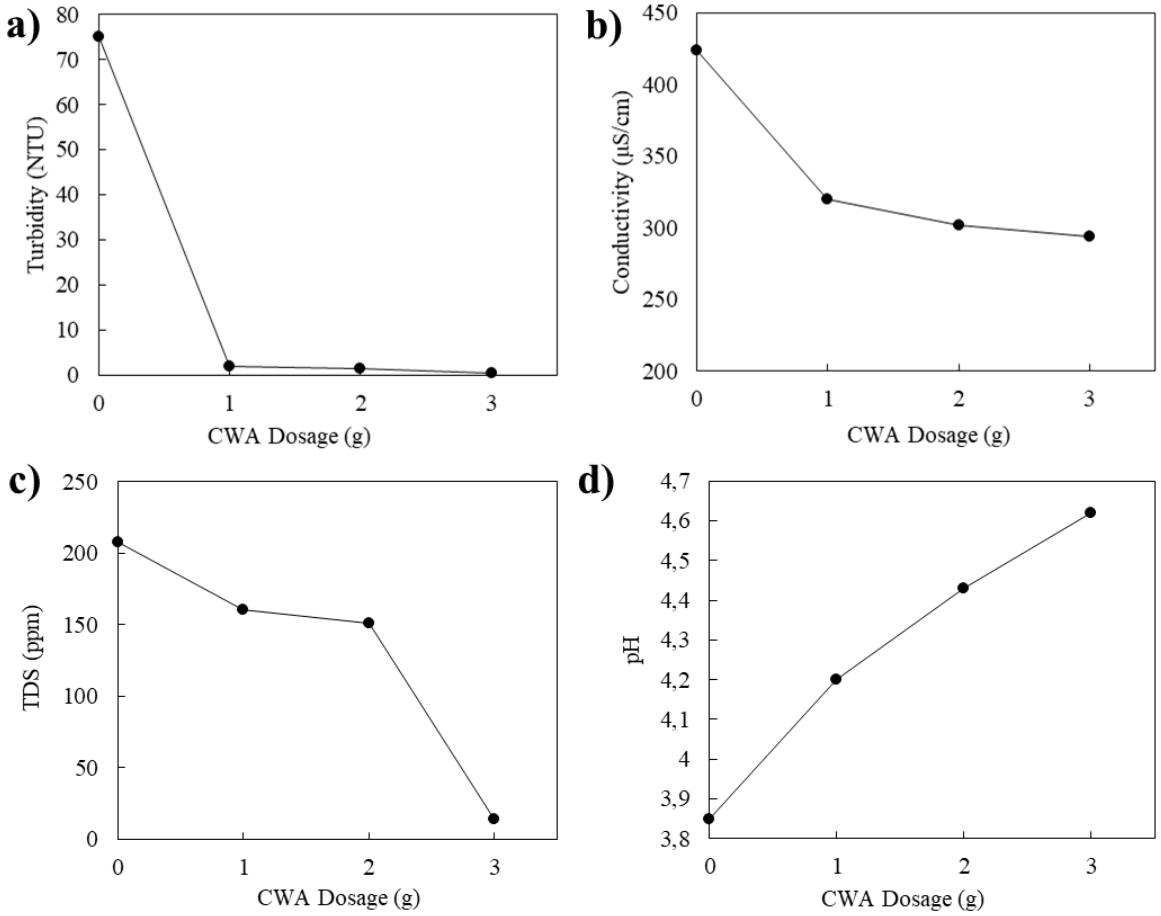

Figure 2. Effect of coffee waste adsorbent (CWA) dosage on peat water parameters: a) Turbidity; b) Conductivity; c) TDS; and d) pH

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Moreover, the *qe* value was initially 9.60 mg/g, subsequently decreased to 5.70 mg/g at 2 g, and then significantly increased to 12.93 mg/g at 3 g. Notably, the intense increase in removal efficiency at 3 g suggested a potential threshold effect, wherein optimal conditions for TDS removal were achieved. This enhancement clearly indicated that a 3g dosage represented an efficient level for overall TDS removal and the effective utilization of the adsorbent material.

The affected improvement in performance at this dosage was attributed to achieving a critical concentration of active sites necessary for effective TDS removal, combined with efficient particle dispersion and surface area availability [29]. The effectiveness of CWA as an adsorbent was particularly notable in its ability to remove a wide range of contaminants, including heavy metals and organic pollutants, thereby improving the overall quality of water [30]. These findings had significant implications for practical applications in peat water treatment, suggesting that while CWA was effective across various dosages, efficient performance was achieved at higher concentrations where both removal efficiency and adsorption capacity were maximized.

3.3 Adsorption Isotherm

The adsorption isotherm is a crucial aspect in designing effective adsorption systems, as it provides valuable insights into the interactions between adsorbates and adsorbents. The Langmuir and the Freundlich isotherm models are widely used to study adsorption processes. The Langmuir model assumes homogeneous monolayer adsorption, whereas the Freundlich model applies to physical and chemical adsorption processes [11]. To determine the applicability of each isotherm model under the previously described experimental conditions, each plot's correlation coefficient (R^2) was used to measure the model's goodness of fit. As shown in Figure 3, a higher R^2 value indicates a better fit between the experimental data and the isotherm model.

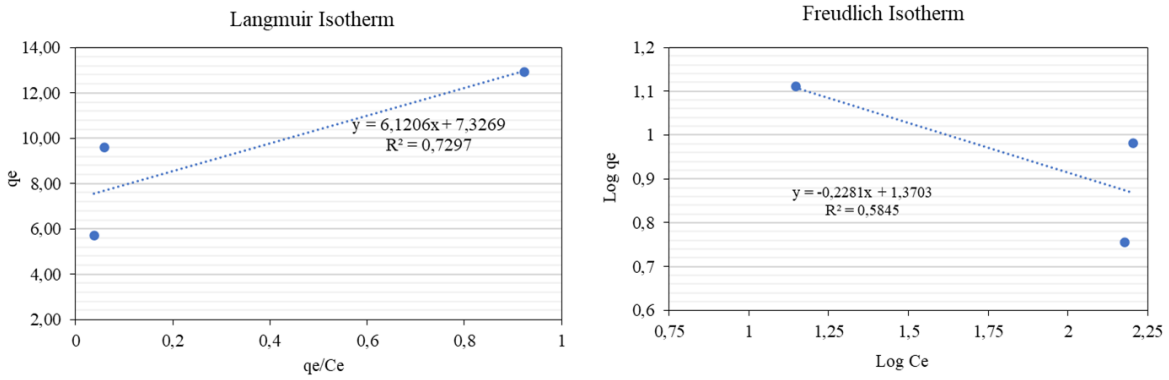

Figure 3. Langmuir & Freudlich plots for adsorption isotherm

Table 1. Parameters of peat water adsorption isotherms fitted with Langmuir and Freundlich models

Sample	Langmuir model			Freundlich model			
	qm (mg/g)	*KL*	R^2	*RL*	*KF*	1/n	R^2
CWA	0.163	0.835	0.730	0.00572	23.461	-4.384	0.585

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The analysis of the isotherm models, summarized in Table 1, revealed that the Freundlich model yielded an R^2 value of 0.5845, with *KF* and *n* values of 23.4606 (L/mg) and –4.3842, respectively. In contrast, the Langmuir model provided a better fit, with an R^2 value of 0.7297, indicating that the adsorption of TDS from peat water onto CWA occurred predominantly on a homogeneous surface with uniform binding sites [13].

The maximum adsorption capacity (q_m) was calculated to be 0.1634 mg/g, while the Langmuir constant (*KL*) was found to be 0.8354 L/mg. The relatively low value of q_m suggests a limited adsorption capacity of CWA, which might be affected by surface area and impurities that could block active sites on the adsorbent [10],[31],[32]. Furthermore, the separation factor (*RL*) was calculated as 0.0057, falling between 0 and 1, thereby confirming that the adsorption process was favorable according to the Langmuir model [33]. This finding aligns with previous studies highlighting the effectiveness of CWA in removing various contaminants, reinforcing its potential for practical applications in wastewater treatment [34],[35].

However, the relatively low R^2 values for both models suggest that additional factors, such as competing ions, pH, and temperature, might have significantly affected the adsorption process, warranting further investigation [27],[36],[37]. This deviation could also stem from the non-linearity in the adsorption behavior. The complex composition of peat water, containing heterogeneous natural organic matter such as humic substances, polysaccharides, proteins, and VOCs, might have resulted in multiple simultaneous adsorption mechanisms that could not be adequately described by single-component isotherm models. The experimental design further reflected the effect of adsorbent dosage rather than the true equilibrium isotherms. Classical isotherm studies typically require varying initial concentrations at a constant adsorbent mass, whereas in this study, the adsorbent mass was varied at a constant initial concentration. The highly non-linear responses observed in the data, such as the sharp drop in turbidity from approximately 75 to 2 NTU between 0 and 1 g of CWA, and similar drastic reductions in TDS, indicated threshold effects and competitive adsorption among different peat water components for the same binding sites. These factors further complicated the adsorption process and contributed to deviations from the ideal behavior assumed in classical isotherm models.

The complex composition of peat water, which may contain various competing ions and organic matter, could have hindered the adsorption efficiency of coffee waste [31],[32]. This complexity necessitates a comprehensive understanding of the interactions between the adsorbent and adsorbate, as well as the environmental conditions under which adsorption occurs. The findings of this study contribute to the growing body of literature supporting the use of agricultural waste, such as spent coffee grounds, as viable adsorbents for wastewater treatment applications [34],[35]. The results indicate that while the adsorption process exhibited a certain degree of heterogeneity, it was predominantly governed by a monolayer adsorption mechanism, as suggested by the Langmuir model. This model posits that adsorbate molecules are adsorbed as a single layer and are homogeneously distributed across the adsorbent surface, with minimal interactions among adsorbed

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molecules. The functional groups (–OH and –COOH) present on the surface of coffee waste provide uniform binding sites with equivalent adsorption energies, enabling each site to accommodate a single molecule of peat water contaminants, including humic substances and VOCs [11],[16],[38]. However, the observed limitations in adsorption capacity and the effect of environmental variables underscore the need for further research to focus on the optimization of coffee waste in peat water treatment applications.

4. Conclusion

This study demonstrated that coffee waste adsorbent (CWA) has potential as an eco-friendly and cost-effective material for improving peat water quality. At an optimal dosage of 3 g per 200 mL, CWA significantly reduced turbidity (99.37%), total dissolved solids (TDS) (93.3%), and conductivity (30.7%), while increasing the pH from 3.85 to 4.62. Improvements in color and odor, as confirmed by sensory evaluation, further support its practical applicability in water treatment. Despite these promising results, several limitations were identified. The maximum adsorption capacity was relatively low (0.1634 mg/g), and although the Langmuir isotherm model provided a better fit than the Freundlich model, it yielded a moderate correlation coefficient (R^2 = 0.7297). This finding suggests that external factors might have significantly affected the adsorption behavior. Furthermore, the experimental design primarily reflected the effects of adsorbent dosage rather than true equilibrium isotherms, with highly non-linear responses indicating threshold effects and potential competitive adsorption among peat water components.

This study provides a foundation for further research aimed at enhancing the adsorption capacity of CWA and assessing its long-term performance under real environmental conditions. Overall, CWA represents a promising alternative for sustainable peat water treatment and waste valorization.

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