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Evaluation of the Adsorption Efficiency of Activated Carbon Derived from Mauritia *flexuosa Seeds* in Coffee Wastewater

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The objective of this study was to evaluate the effect of activated carbon derived from *Mauritia flexuosa* seeds on the adsorption of phenolic compounds (tannins and lignins) present in honey waters generated during the processing of *Coffea arabica*. This research seeks to contribute to reducing the environmental impacts associated with the discharge of these effluents into natural water bodies. The variables evaluated included the activated carbon produced from *Mauritia flexuosa* seeds and the adsorption capacity for phenolic compounds. Adsorption efficiency was determined by applying different concentrations of the activated carbon, prepared using two chemical activating agents, to wastewater samples. The data were analyzed under varying operational conditions, in which adsorbent dosage, mixing speed, and contact time influenced removal performance. The results showed that the activated carbon produced with phosphoric acid exhibited higher adsorption efficiency than the carbon activated with sodium hydroxide, demonstrating its potential for application in the treatment of coffee-processing wastewater in agricultural regions.

1. Introduction

Coffee cultivation is a major global agricultural activity, particularly in tropical regions where climatic conditions favor its production (Craparo et al., 2015). However, the processing of coffee cherries generates liquid effluents, commonly referred to as coffee wastewater or “honey waters,” which possess high concentrations of organic matter and phenolic constituents such as tannins and lignins (Aswathi et al., 2022). When discharged untreated into natural water bodies, these effluents cause reductions in dissolved oxygen, pH alterations, water darkening, and eutrophication, thereby disrupting critical biological processes in aquatic organisms (Molla et al., 2025; Pino-Otín et al., 2023; Zhong et al., 2018). Despite these severe environmental threats, wastewater treatment systems in many coffee-producing regions of Latin America remain underdeveloped due to economic, geographic, and technological constraints, limiting the adoption of low-cost solutions (Montes et al., 2023). In Peru, the Department of San Martín—particularly districts like Moyobamba—is recognized as a primary coffee-producing area where traditional bean washing near watercourses leads to direct discharges, resulting in pronounced water discoloration and adverse effects on aquatic biota (Aguila et al., 2018; Ruprecht et al., 2021). Concurrently, this region contains abundant forest resources, including Mauritia flexuosa (“aguaje”), whose seeds are typically discarded as waste despite representing a promising and sustainable precursor for the development of low-cost adsorbent materials (Quinteros-Gómez et al., 2021).
The use of *Mauritia flexuosa* seeds as a precursor for activated carbon production provides a sustainable and economically viable approach, as it converts a locally available agricultural by-product into an adsorbent capable of removing contaminants from coffee wastewater (Nilavazhagi and Felixkala, 2021). The aim of this study is to

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evaluate the adsorption efficiency of activated carbon obtained from *Mauritia flexuosa* seeds for the removal of phenolic compounds present in wastewater generated during *Coffea arabica* processing. The scope of the investigation includes the preparation and physicochemical characterization of the adsorbent and the assessment of operational parameters influencing adsorption performance.

This study addresses the need for low-cost, locally adaptable treatment strategies in rural areas of the Peruvian high jungle, where coffee wastewater contamination is closely linked to traditional agricultural practices. By proposing an environmentally responsible alternative based on locally available natural resources, this work contributes to mitigating environmental impacts and promoting sustainable production in the San Martín region.

2. Materials and Methods

2.1 Preparation of activated carbon

The precursor material, *Mauritia flexuosa* seeds, was dried in an oven (DON-65, BIOEVOPEAK) at 95 °C for 24 h to a constant weight, crushed, and sieved through a No. 30 mesh (500 µm). Two chemical activation methods were employed:

Activation with H_3PO_4: The sieved precursor was impregnated with phosphoric acid (H_3PO_4) in a 1:1 mass ratio, allowed to rest for 24 h at room temperature, and carbonized in a muffle furnace (FO110CR, YAMATO) under anaerobic conditions by raising the temperature to 600 °C at a rate of 10 °C/min for 30 min. The resulting activated carbon was washed repeatedly with distilled water until reaching a neutral pH, dried at 110 °C, and sieved through a No. 30 mesh.

Activation with NaOH: The precursor was first carbonized at 300 °C for 1 h to produce charcoal, ground to a particle size of < 200 µm, mixed with sodium hydroxide (NaOH) in a 1:4 mass ratio, and activated at 700 °C for 1 h in the muffle furnace. The product was neutralized with distilled water, dried, and sieved similarly.

2.2 Characterization of Activated Carbon

The physicochemical properties of the activated carbons were characterized using an analytical balance (PGW 753i) for mass measurements. For the methylene blue index, 0.5 g of carbon was mixed with a 100 mg/L methylene blue solution, agitated for 30 min using a magnetic hotplate stirrer, filtered, and the filtrate absorbance was measured at 664 nm. For the iodine index, 1 g of carbon was treated with a 0.1 N iodine solution and titrated with standardized sodium thiosulfate (Na2S2O3). Surface morphology and pore structure were examined using high-resolution scanning electron microscopy (SEM, PRISMA).

2.3 Adsorption Experiments

Coffee wet-processing wastewater was collected from local processing units, where the initial pH (≈3.8) and the concentration of tannins and lignins (186 mg/L) were measured; the latter was determined using a spectrophotometer (DR 1900, HACH) via the tyrosine method (HACH 8193) after a 1:30 dilution, as the actual concentration exceeded the method's linear range (0.2–7.0 mg/L). Adsorption assays were carried out in a jar tester at the natural wastewater pH, without adjustment, and at room temperature (≈25 ± 2 °C) monitored with a portable pH meter (HQ1110, HACH) without thermal control.

Batch experiments were conducted under a full factorial design evaluating adsorbent dosage (1.0–2.0 g/50 mL), agitation speed (100–300 rpm), and contact time (1–3 min), a range based on previous studies regarding carbons derived from lignocellulosic precursors (Azabache et al., 2021). All experiments were performed in duplicate (n = 2) for each combination, totaling 108 assays. The removal percentage was determined using Eq(1):

$$\% \, Removal = \frac{C_i - C_f}{C_i} \times 100 \quad (1)$$

where C_i = initial concentration and C_f = final concentration.

2.4 Statistical analysis

Data were analyzed using ANOVA with SPSS software to evaluate the significance of the independent variables (activator type, carbon dose, stirring speed, and contact time) on adsorption efficiency at a 95% confidence level.

3. Results

In Table 1, the results of the characterization of activated carbon through methylene blue adsorption are presented. This compares the activated materials with H_3PO_4 and NaOH, based on the initial and final concentrations of the dye, absorbance, and removal percentage, allowing for the evaluation of the influence of the activating agent on the adsorptive efficiency.

The observed difference between both adsorbents is quantitatively significant and supports the previously discussed mechanisms. The activated carbon with H_3PO_4 reduced the initial methylene blue concentration from 100 mg/L to only 0.2376 mg/L, achieving a removal of 99.76%, while the activated carbon with NaOH only reduced the concentration to 42.911 mg/L, which corresponds to a 57.09% removal. This gap of over 42 percentage points demonstrates that the microporous structure generated by H_3PO_4 facilitates greater diffusion and retention of the dye, consistent with the findings reported by Zhou et al. (2022), who noted that phosphoric activation creates carbon matrices with denser active sites and greater affinity for cationic compounds.

Table 1: Results of activated carbon characterization with methylene blue

Activating agent	Activated carbon dose (g)	Initial concentration (mg/L)	Absorbance	Final concentration (mg/L)	% Removal
H_3PO_4	0.5	100	0.409	0.2376	99.76
NaOH	0.5	100	0.840	42.911	57.09

Table 2 shows the iodine index results for activated carbon. Factors A and B, based on solution normality and iodine's equivalent weight, are constant for both materials, ensuring consistent conditions. Parameter C, representing iodine remaining in solution after adsorption, inversely indicates adsorption capacity.
The NaOH-activated carbon had a C value of 0.098, higher than the 0.066 for the H_3PO_4-activated carbon, suggesting lower iodine adsorption. Consequently, the iodine index for H_3PO_4-activated carbon was 808.544 mg/g, compared to 585.147 mg/g for NaOH-activated carbon, a difference of over 223 mg/g. These results indicate greater microporosity in the phosphoric acid-activated material, in line with Yorgun and Yildiz (2015), who found iodine indices above 700 mg/g for such materials.

Table 2: Titration parameters and iodine index values of activated carbons with H_3PO_4 and NaOH

Activating agent	Sample mass (g)	Volume of reagent $Na_2S_2O_3$ (ml)	A=N_1x126.93	B=N_2x126.93	C=N_2xml thiosulfate/25	Iodine index "X/M" (mg/g)
H_3PO_4	1	16.5	1269.3	12.693	0.066	808.544
NaOH	1	24.5	1269.3	12.693	0.098	585.147

The coffee wastewater employed in this study exhibited a pH of ≈3.8 and an initial tannin and lignin concentration of 186 mg/L.
Figure 1 presents the micrographs obtained by scanning electron microscopy (SEM) of the activated carbon using H_3PO_4, where a highly developed surface with large-diameter pores and interconnected cavities is observed, allowing the analysis of the effect of phosphoric activation on the formation of an open porous structure. The SEM micrographs reveal a highly developed surface structure characterized by large-diameter pores, including cavities measuring 89.86 µm, 59.65 µm, and 30.58 µm. This morphological pattern aligns with the mechanisms of H_3PO_4 activation, where simultaneous dehydration, the formation of phosphorylated complexes, and carbon matrix expansion generate larger pores with thinner walls. Consistent with Nahil et al. (2012), phosphoric acid promotes macropore opening and interconnection, thereby increasing internal accessibility and enhancing the adsorbent's capacity to interact with larger molecules.

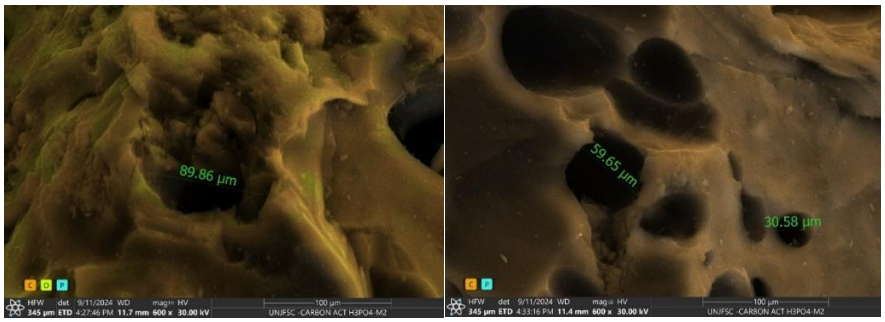

Figure 1: SEM scanning electron microscopy (Activated Carbon - H_3PO_4).

Figure 2 shows the SEM micrographs of the activated carbon obtained through NaOH, revealing a more compact surface and a distribution of smaller and more heterogeneous pores, which allows for the evaluation of morphological and structural differences induced by alkaline activation compared to the material activated with H_3PO_4.

In contrast, the SEM images display a more compact surface with notably smaller pores, ranging from 53.96 µm to 6.64 µm, which demonstrates a more closed and less heterogeneous pore distribution compared to the material activated with H_3PO_4. Activation with NaOH tends to generate structures based on more controlled surface reactions, where micropores and mesopores predominantly form as a result of the alkaline degradation of lignocellulose and the sequential removal of volatile compounds. This behavior has been documented by Yang and Lua (2003), who observed that caustic activation produces finer, less interconnected pores, limiting the diffusion of larger molecules.

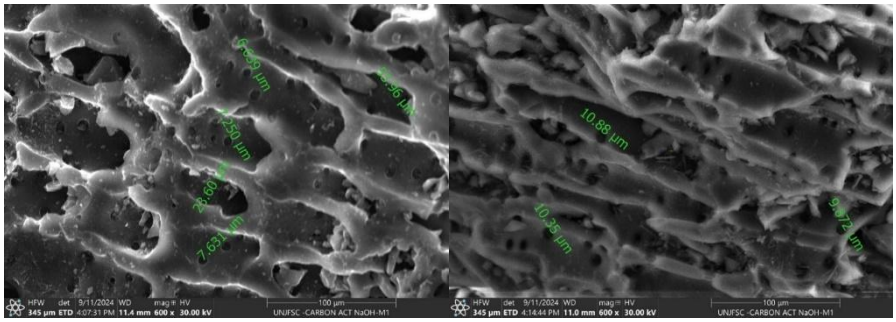

Figure 2: SEM scanning electron microscopy (Activated Carbon – NaOH).

SEM revealed larger pores in H_3PO_4-activated carbon (89.86 µm) than in NaOH-activated carbon (53.96 µm), suggesting a more open structure favourable for bulky molecule adsorption. Nevertheless, SEM provides qualitative information and does not permit precise quantitative characterisation of porosity; therefore, the structure–adsorption relationship should be interpreted with caution.

Figure 3 shows the variation in the final concentration of tannins and lignins as a function of the contact time and the dose of activated carbon impregnated with H_3PO_4 (1, 1.5, and 2 g), allowing the evaluation of the influence of the adsorbent amount and the agitation conditions on the removal efficiency.

With 1 g of activated carbon impregnated with H_3PO_4 (Figure 3a), the lowest final concentration obtained was 58.5 mg/L at a contact time of 2 minutes and 100 rpm. In contrast, with 1.5 g (Figure 3b), the lowest final concentration in the set (39 mg/L) was achieved at 1 minute and 300 rpm, showing a higher adsorption capacity at this operational point. Finally, with 2 g of activated carbon (Figure 3c), the minimum recorded value was 45.25 mg/L at 3 minutes and 100 rpm. These results confirm that the 1.5 g dose optimizes the adsorbate-adsorbent interaction and align with studies that report that activation with H_3PO_4 promotes highly accessible and efficient structures for the retention of phenolic compounds (Megherbi et al., 2024). The overall analysis shows that the lowest final concentration was 39 mg/L using 1.5 g of activated carbon, which corresponds to 79.03% adsorption relative to the initial concentration (186 mg/L).

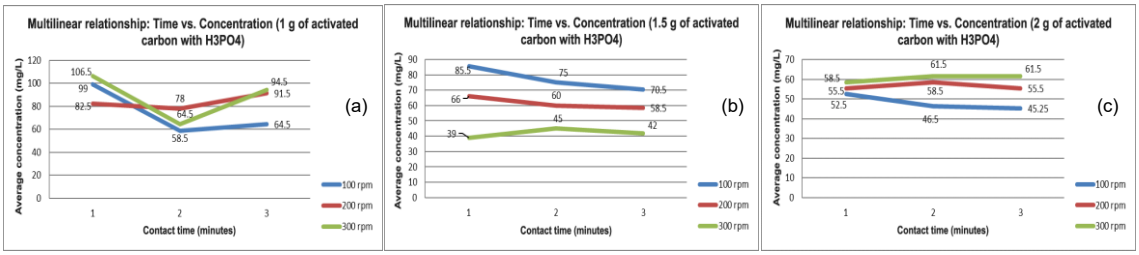

Figure 3: (a) average final concentration (1 g of activated carbon – H_3PO_4), (b) average final concentration (1.5 g of activated carbon – H_3PO_4), (c) average final con centration (2 g of activated carbon – H_3PO_4).

Figure 4 shows the relationship between the final concentration of tannins and lignins, contact time, and the dose of activated carbon modified with NaOH (1, 1.5, and 2 g), allowing the analysis of the effect of alkaline activation and the amount of adsorbent on the adsorptive behavior of the material.

For 1 g of adsorbent (Figure 4a), the lowest concentration was 109.5 mg/L at 1 minute and 100 rpm, while with 1.5 g (Figure 4b), the lowest value in the set (63 mg/L) was recorded at 200 rpm and 1 minute, demonstrating

the highest adsorption capacity among the three doses. In contrast, with 2 g of activated carbon (Figure 4c), the minimum concentration was 88.5 mg/L at 300 rpm and 1 minute, suggesting that excessive increases in mass may cause particle agglomeration and a reduction in the active area, a phenomenon previously reported in alkaline systems (Qiu et al., 2022).

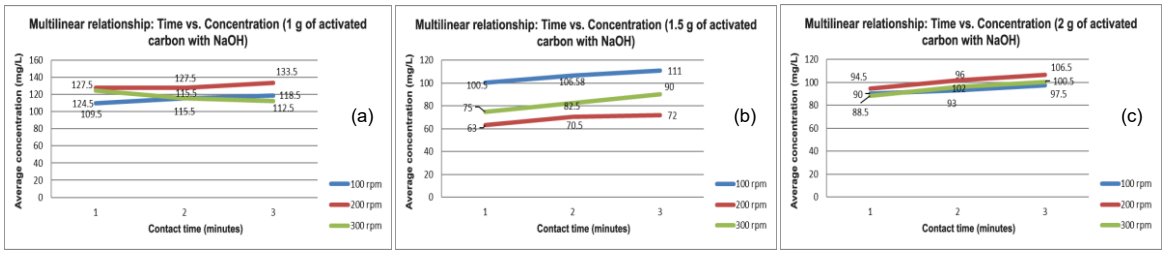

Figure 4: (a) average final concentration (1 g of activated carbon – NaOH), (b) average final concentration (1.5 g of activated carbon – NaOH), (c) average fi nal concentration (2 g of activated carbon – NaOH).

The maximum removal of tannins and lignins was 79.03% (1.5 g, 300 rpm, 1 min) using H_3PO_4-activated carbon, where the 1:30 dilution (186→6.2 mg/L) required for analytical purposes reduces ionic strength and competition for active sites, which could favor adsorption compared to real effluents (Moreno-Castilla, 2004); therefore, these results correspond to controlled conditions and require validation in real effluents.

Table 3 presents the results of the analysis of variance (ANOVA) applied to the regression model explaining the removal percentage. The obtained F-statistic (F = 52.575) is considerably high and is associated with a p-value < 0.001, which is well below the conventional significance threshold (α = 0.05). Based on this criterion, the hypothesis that at least one of the model coefficients contributes significantly to the variation observed in the response is supported. This result indicates that the regression model, as a whole, is statistically significant and therefore suitable for describing the relationship between the removal percentage and the independent variables considered: time, speed, carbon weight, and type of activating agent.

Table 3: Analysis of variance (ANOVA) of the linear regression model applied to the percentage of removal.

Source of variation (Model)		Sum of squares	Degrees of freedom	Mean Square	F Calculated	Sig.
1	Regression	13318.724	4	3329.681	52.575	<0.001[a]
	Residue	6523.141	103	63.331		
	Total	19841.865	107			

[a] Predictors: (Constant), Time (min), Speed (rpm), Carbon Weight (g), Activating Agent H_3PO_4 and NaOH

The ANOVA results (Table 3) confirmed the statistical significance of the model (F = 52.575, p < 0.001). All four main effects were statistically significant: activating agent (p < 0.001), adsorbent dosage (p < 0.001), stirring speed (p < 0.001), and contact time (p < 0.001). Regarding two-way interactions, only adsorbent dosage × activating agent (p = 0.002) and stirring speed × contact time (p = 0.005) were significant (p < 0.05), whereas all other interactions were not (p > 0.05).

4. Conclusions

H_3PO_4-activated carbon derived from Mauritia flexuosa seeds outperformed NaOH-activated carbon, achieving 99.76% methylene blue removal and an iodine number of 808.544 mg/g. SEM revealed a more open porous structure with larger pores, consistent with its enhanced adsorption of tannins and lignins (79.03% at 1.5 g, 300 rpm, 1 min). Nevertheless, SEM provides qualitative morphological information and does not permit precise quantitative characterisation of porosity. The statistical significance of the operational variables was confirmed by ANOVA (p < 0.001). The rapid kinetics (1–3 min) and the abundance of M. flexuosa seeds in the Amazon region favour potential scaling; however, pilot-scale validation is required. Based on the optimal conditions (1.5 g/50 mL), an estimated 30 kg of activated carbon per m^3 of wastewater would be required. Future studies should include BET surface area analysis and economic feasibility assessments to support large-scale implementation.

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