



Comparison of conventional pyrolysis and microwave irradiation to transform an amazonic waste into activated carbon for organic contaminants adsorption

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Abstract

Ucuuba (*Virola surinamensis*) waste was converted into efficient activated carbons, aiming to promote gains and greater sustainability for the riverside cooperatives in Amazonia. The conversion was carried out by conventional pyrolysis (ACP) and microwave irradiation (ACM), and the activated carbons were used to uptake tartrazine yellow (TY) and methylene blue (MB) from water. The results showed that the material produced by the conventional process (ACP) had an S_{BET} of $587.38 \text{ m}^2 \text{ g}^{-1}$ and a predominance of micropores combined with mesopores. These features led to higher adsorption capacities (169.32 mg g^{-1} for TY and 671.99 mg g^{-1} for MB), but lower potential for reuse (3 times). Besides, the conventional process requires more time and reagents. Parallely, the material developed by microwave (ACM) exhibited an S_{BET} of $88.11 \text{ m}^2 \text{ g}^{-1}$ and a mesoporous pore-size classification. Consequently, the adsorption capacities were lower (MB=504.16 and TY=103.58 mg g^{-1}). Still, the reuse potential was better (5 times). In addition, ACM requires only 90 s of heat treatment and uses fewer reagents for preparation. It was demonstrated that ACP and ACM from Ucuuba (*Virola surinamensis*) wastes were developed in different ways, each with its own advantages and drawbacks. However, both materials were efficient and helped sustain the riverside cooperatives in the Brazilian Amazonia.

Keywords Ucuuba (*Virola surinamensis*) · Methylene blue · Tartrazine yellow · Amazonic wastes · Microwaves

1 Introduction

The Amazon rainforest, which occupies the majority of its territory in the northern region of Brazil, boasts a great biodiversity of plants [1, 2]. Amazonian cooperatives, farmers, and artisans are responsible for the sustainable exploitation of biodiversity and the management of the region's natural resources [3]. In this way, Amazonian biodiversity has been widely exploited by the pharmaceutical and cosmetics industry. Among the plant species present in the Amazon is Ucuuba, also known by its popular name, *Virola Surinamensis*. It is commonly found in flooded areas, on the banks of rivers. The Ucuuba is a large tree; its fruits (almonds) are composed of approximately 55 to 76% fat. It has medicinal properties and is widely used in the pharmaceutical and cosmetic industries [4–6]. Many types of waste, such as bagasse, shells, hardware, and others, are generated during the processing stages of obtaining products from Amazon plant species. A large part of this residual mass is rich in

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lignocellulosic constituents [7]. Therefore, the development of new materials, for example, activated carbon, from this waste increases the value of Amazonian natural resources and facilitates the reuse of discarded materials [8, 9].

Activated carbon is an amorphous carbonaceous material with several advantageous properties, including a high surface area, porous structure, excellent adsorption capacity, and high thermal stability [10, 11]. This material has been employed as a catalyst support, an electrode in supercapacitors for energy and hydrogen storage, a substitute for carbon black filler in rubber soles, and as an adsorbent in the treatment of liquids and gases, among other applications [10, 12, 13]. The traditionally used method, which is quite effective in obtaining activated carbons with excellent properties, is pyrolysis. This method involves carbonizing the raw material at a high temperature, followed by an activation step, which can be either physical or chemical [10, 14]. However, both of them consumed too much energy [10, 15]. Another promising method that has been employed to produce activated carbon is microwave heating. This technique utilizes less energy in a shorter time heating process [10, 14, 15], reducing energy consumption by approximately 60–80% [16, 17]. Microwave irradiation is a high-efficiency heating method [18–20], characterized by specific features such as rapid, selective, and volumetric heating, as well as nonthermal effects on chemical reaction rates [17, 18, 21].

Adsorption using activated carbon is one of the most widely used methods for water treatment, particularly in the removal of pharmaceuticals, heavy metals, dyes, and other pollutants from liquid effluents [19, 20, 22]. This technique is attractive due to its low cost and simplicity of application [22–24]. The synthetic dyes, such as methylene blue and tartrazine yellow, are commonly used in the textile, leather, cosmetics, paper, printing, and plastics industries [22, 25]. Dyes are not biodegradable; therefore, they cause serious problems and harm the photosynthetic activity in aquatic environments [22, 26]. Some of the side effects observed in humans include allergies, dermatitis, and skin irritation [26, 27], and can also lead to genetic mutations [22, 28].

Amazonian biomasses have been used to develop activated carbons by chemical and physical activations, and pyrolysis to treat effluents, such as Brazil nut and andiroba residues to remove iron and manganese [7], murumuru residues for anti-inflammatory drugs removal [29], garapa residue to adsorb methylene blue and phenol [30], Brazil nut residues and palm kernel cake for cadmium and copper removal, and açai residues to remove herbicides, pharmaceuticals and metals [27, 31–34]. Studies on using waste from the Amazon region to obtain microwave- and pyrolysis-activated carbon for application as an adsorbent material are scarce, and the literature does not report the use of Ucuuba residue as a precursor. Studies on the production of

microwave-activated carbon have utilized waste from indigenous *Acacia etbaica* tree branches [35], Salacca peel [10], pineapple peel [36], sugarcane bagasse [37], and almond shell [38] for methylene blue removal. Gomez-Avilés et al. [39] developed activated carbons from microwave-assisted FeCl_3 -activation of lignin for acetaminophen adsorption. Cruz et al. [40] developed activated carbons from cupuaçu shell and Brazil nut shell residues obtained in the Amazon region by microwave irradiation followed by a carbonization step at 880 °C for methane adsorption.

This study aims to add value to plant waste from extractive activities in the Amazon region, Ucuuba (*Virola surinamensis*), developing new products, such as activated carbon from Ucuuba waste, through different production routes (microwave irradiation and pyrolysis), for application in the adsorption of contaminants present in liquid effluents and to evaluate its performance by adjusting mathematical models to experimental data through kinetic, equilibrium and thermodynamic studies.

2 Materials and methods

2.1 Reagents

The reagents used were analytical-grade hydrochloric acid and sodium hydroxide for pH adjustment. The dyes were tartrazine yellow ($\text{C}_{16}\text{H}_9\text{N}_4\text{Na}_3\text{O}_9\text{S}_2$, molecular weight of 534.4 g mol⁻¹, solubility in water of 2.0×10^5 mg L⁻¹ at 25 °C, and 425 nm of wavelength) [41, 42] and methylene blue ($\text{C}_{16}\text{H}_{18}\text{ClN}_3\text{S}$, molecular weight of 319.9 g mol⁻¹, solubility in water of 4.36×10^4 mg L⁻¹ at 25 °C, and 664 nm of wavelength) [35, 36] from Sigma Aldrich (São Paulo, Brazil).

The residual concentration of the dyes was quantified using a standard curve with a concentration range of 1 to 30 mg L⁻¹ at their respective wavelengths, as measured by a UV/Visible spectrophotometer (BEL Engineering, UV M51).

2.2 Conventional pyrolysis and microwave irradiation of Ucuuba wastes

The lignocellulosic biomass was obtained from an Amazonian riverside cooperative near Santarém City, Pará state. It consists of Ucuuba (*Virola surinamensis*) waste after the extraction of some products for the pharmaceutical industry. The raw material was comminuted to a particle size of less than 60 mesh (0.25 mm) and oven-dried at 50 °C overnight for characterization and processing.

For the preparation of activated carbon by conventional pyrolysis (ACP), 20 g of Ucuuba residue was mixed with

20 g of zinc chloride (ZnCl_2). The mixture was then moistened with distilled water until a paste formed. The paste was placed in a petri dish and dried at 60 °C for 24 h in an oven. After drying, the mixture was ground into a homogeneous substance. After this step, 33 g of the mixture was added to a quartz reactor, which was placed in a furnace and subjected to a heating rate of 10 °C min^{-1} (from 25 to 700 °C). The sample was pyrolyzed at 700 °C for 2 h in a N_2 atmosphere. An acid wash was performed on the material obtained from pyrolysis by mixing the pyrolysis product with 250 mL of 6 mol L^{-1} HCl solution. Afterwards, the material was washed with distilled water until it reached neutral pH.

For the preparation of activated carbon by microwave irradiation (ACM), 20 g of powder residue and 20 g of NaOH pellets were mixed. To increase the contact between the solid particles and NaOH, the mixture was slightly humidified with water using a manual spray bottle. The material was placed inside a crucible with a lid and exposed to microwave irradiation (Electrolux, 2.4 GHz) of 1000 W for 1.5 min (90 s) under a static and limited air atmosphere. After cooling to room temperature, the product was washed with water until the pH reached neutrality. Afterwards, it was dried at 100 °C for 10 h. The activated carbon obtained by microwave irradiation was denominated as ACM.

2.3 Characterization of Ucuuba wastes, ACP, and ACM

The chemical composition of the Ucuuba biomass residue was determined using standardized analytical procedures. The extractives content was quantified according to TAPPI T204 cm-97, using an ethanol/benzene mixture (1:2 v/v) as the extraction solvent. The acid-insoluble lignin (Klason lignin) was determined following TAPPI T222 om-02. The contents of moisture, cellulose, and hemicellulose were determined using a modified Van Soest method, as described by Silva and Queiroz (2009). The ash content was determined by gravimetric analysis after calcination of the biomass in a muffle furnace until constant mass. The solid materials (Ucuuba wastes, ACP, and ACM) were characterized by FTIR (Shimadzu, IR Prestige 21), to identify the functional groups, in the range of 400–4500 cm^{-1} with 45 scans per spectrum and 2 cm^{-1} of resolution, XRD (Rigaku, Miniflex 300), to identify the crystalline and amorphous nature with a Cu $\text{K}\alpha$ radiation ($\lambda = 1.5418 \text{ \AA}$) at 30 kV and 10 mA, by scanning step over the range of 5–99.98°. The N_2 adsorption-desorption isotherm was obtained by degassing the AC samples for 24 h at 150 °C under vacuum and analyzed by the BET method (Micromeritics, ASAP 2020) to estimate the specific surface area. The thermal stability of the samples was analyzed by TGA (SHIMADZU TGA-50, Kyoto, Japan), with a N_2 flow rate of 20 $\text{mL}\cdot\text{min}^{-1}$

and a heating rate of 10 °C $\cdot\text{min}^{-1}$. The adsorbent surface morphology was analyzed by SEM (Mira 3, Tescan, Czech Republic) at different magnifications. Also, the point of zero charge (pH_{pzc}) of ACP and ACM was analyzed by adding 20 mL of a 0.05 mol L^{-1} NaCl solution to 50 mg of adsorbent, with a pH range of 2 to 10, and stirring at 150 rpm and 25 °C for 48 h [37]. After the contact time ended, the liquid phase was separated from the solid phase using filter paper. The pH of the solutions before (pH_i) and after (pH_f) the adsorption process was analyzed using a digital pH meter (AKSO, AK90). Finally, Standard methods were employed to quantify the content of moisture, ashes, extractives, lignin, cellulose, and hemicellulose in the Ucuuba wastes [12, 16, 33, 43].

2.4 Adsorption experiments and modeling

The adsorption experiments were carried out in a batch. A 1000 mg L^{-1} stock solutions of tartrazine yellow and methylene blue were prepared. The adsorbent dosage used was 0.5 g L^{-1} with 20 mL of dye solution in a temperature-controlled shaker (Solab, SL-222) at 150 rpm. For the study of the pH effect, the pH of the initial solutions was adjusted to a range of 2 to 10 over 2 h, with an initial concentration of 20 mg L^{-1} . After the adsorption process, the liquid phase was separated from the solid phase by filtration, and the final concentration was determined using a UV/Visible spectrophotometer at its respective wavelength. The adsorption capacity of ACM and ACP, Q (mg g^{-1}), was calculated by Eq. (1), and the removal efficiency E (%) by Eq. (2).

$$Q = \frac{V(C_0 - C_e)}{m} \quad (1)$$

$$E = \frac{C_0 - C_e}{C_0} 100\% \quad (2)$$

Where C_0 is the initial, and C_e the equilibrium contaminant concentration (mg L^{-1}), V is the volume of solution (L), and m is the mass of adsorbent (g).

For the kinetic study, the time of adsorption was varied from 0 to 420 min, with an initial solution concentration of 20 mg L^{-1} at the optimal pH condition. The kinetic models used to adjust the experimental data were Pseudo-First Order (PFO) [44], Pseudo-Second Order (PSO) [45], and Bangham, which are represented by Eqs. (3), (4), and (5):

$$q_t = q_e(1 - \exp(-k_1 t)) \quad (3)$$

$$q_t = \frac{q_e^2 (k_2 t)}{(1 + q_e k_2 t)} \quad (4)$$

$$q_t = q_e(1 - \exp(-k_B t)^{n_B}) \quad (5)$$

Where q_t is the adsorption capacity as a function of time (mg g^{-1}), t is the time (min), k_1 (min^{-1}), k_2 ($\text{g mg}^{-1} \text{min}^{-1}$), and k_B (min^{-1}) are the pseudo-first order, pseudo-second order, and Bangham rate constants, and n_B is the Bangham exponent. q_e is the predicted adsorption capacity at equilibrium (mg g^{-1}).

The equilibrium isotherm study was performed by varying the initial concentration of the solution from 0 to 450 mg L^{-1} . The experiments were conducted until equilibrium was reached, and the mathematical models used were the Langmuir, the Freundlich, and the BET models, represented by Eqs. (6), (7), and (8) [43]. The Gibbs free energy (ΔG^0) was estimated using Eqs. (9) and (10) [43].

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e} \quad (6)$$

$$q_e = K_F C_e^{1/n} \quad (7)$$

$$q_e = \frac{q_{BET} K_1 C_e}{(1 - K_2 C_e)(1 - K_2 C_e + K_1 C_e)} \quad (8)$$

$$\Delta G^0 = -RT \ln K_e \quad (9)$$

$$K_e = K m_{\text{Adsorbate}} \quad (10)$$

where q_m is the maximum adsorption capacity (mg g^{-1}), K_L is the Langmuir constant (L mg^{-1}), K_F the Freundlich constant ($\text{mg g}^{-1} (\text{mg L}^{-1})^{1/n_F}$ and $\frac{1}{n_F}$ the equilibrium constant is indicative of adsorption intensity and associated with the heterogeneity of the adsorbent surface. K_1 , K_2 are the BET constants (L mg^{-1}) and q_{BET} is the BET adsorption capacity (mg g^{-1}). R is a gas constant ($8.314 \text{ J mol}^{-1} \text{K}^{-1}$), T is an absolute temperature (K), K_e the thermodynamic equilibrium constant (-), K , the constant of the best adjustment for experimental data (L mg^{-1}), and $m_{\text{adsorbate}}$ (mg mol^{-1}) is the molecular weight of the adsorbate. Equation (10) considers infinite dilution with an activity coefficient equal to unity and standard concentration of 1 mol L^{-1} .

The determination coefficient (R^2), adjusted coefficient of determination (R^2_{adj}), Average Relative Error (ARE), Akaike information criterion (AIC), and Corrected Akaike information criterion ($AIC_{corrected}$) values were calculated by Eqs. (11), (12), (13), (14), and (15), respectively, to evaluate the adjustment of the mathematical models to the experimental data.

$$R^2 = \left(\frac{\sum_i^n (q_{i,exp} - \bar{q}_{i,exp})^2 - \sum_i^n (q_{i,exp} - \bar{q}_{i,model})^2}{\sum_i^n (q_{i,exp} - \bar{q}_{i,exp})^2} \right) \quad (11)$$

$$R^2_{adj} = 1 - \left[\frac{(1 - R^2)(n - 1)}{n - k - 1} \right] \quad (12)$$

$$ARE = \frac{100}{n} \sum_1^n \left| \frac{q_{i,model} - q_{i,exp}}{q_{i,exp}} \right| \quad (13)$$

$$AIC = n \ln \frac{SSE}{n} + 2k \quad (14)$$

$$AIC_{corrected} = AIC + \frac{(2k(k + 1))}{(n - k - 1)} \quad (15)$$

where $q_{i,exp}$ is the experimental adsorption capacity, $\bar{q}_{i,exp}$ is de average of each adsorption capacity, $q_{i,model}$ is the predicted value, n is the quantity of experiments, k is the number of parameters in the model, and SSE is the sum of square error.

2.5 Desorption and reuse

Desorption and reuse tests were carried out to verify the suitability of the ACP and ACM adsorbents. The chemical desorption method was used, with 0.5 mol L^{-1} NaOH as the eluent for tartrazine yellow and 0.5 mol L^{-1} HCl for methylene blue. Consecutive tests of adsorption-desorption were performed. Adsorption was carried out under the best conditions for each dye, using 1 L of solution. Desorption was performed by inserting 1 g of dye-loaded adsorbent into 50 mL of eluent solution. The mixture was stirred at 200 rpm and 298 K for 2 h. The final dye concentration was determined using a UV/Visible spectrophotometer. The results were evaluated in terms of adsorption capacity (Q , mg g^{-1}) in each cycle.

3 Results and discussion

3.1 Main features of Ucuuba wastes, ACP, and ACM

The chemical characterization of the Ucuuba wastes revealed values of 7% moisture, 45% extractives, 10% cellulose, 3% hemicellulose, 24% lignin, and 8% ash. This composition shows promising potential for the production of activated carbon. The high extractive content favors volatilization during high-temperature thermal processes, contributing to both the initial pore formation and the increase in calorific value [46]. The attractive lignin content confers greater thermal stability due to its aromatic structure, resulting in higher yields in the production of activated carbon. Despite the low cellulose and hemicellulose contents, which could limit mesopore formation, studies indicate that

chemical or physical activation processes compensate for this restriction, promoting greater development of surface area and porosity [47]. Moderate moisture (7%) can favor activated carbon yield without compromising carbon quality. In comparison, the ash content (8%) warrants attention, as it can reduce the surface area but also confer additional properties in specific applications, such as metal ion adsorption or soil conditioning.

Figure 1 shows the nitrogen adsorption-desorption isotherm of ACM (a) and ACP (b). Figure 1(a) resembles the type IV isotherms, according to the IUPAC classification, which are typical of mesoporous materials (pore diameter from 2 to 50 nm). In Figure (a), the fact that the isotherm is no longer nearly horizontal near $P/P_0=1$ suggests the presence of macropores. At low relative pressures ($P/P_0 < 0.2$), an inflection point is observed, indicating a gradual adsorption process that suggests the formation of a monolayer of gas molecules on the material's surface. From the inflection point onwards, the amount of adsorbed nitrogen increases continuously with increasing relative pressure, due to the formation of multiple layers of adsorbed molecules. Therefore, the behavior of the isotherm suggests not only a fluid-surface attraction, but also attraction between the fluid molecules. This formation of multiple layers reflects the open nature of the material surface. A very characteristic form of the type IV isotherm is the hysteresis loop that is associated with the occurrence of pore condensation. It is possible to observe in Fig. 1 (a) a hysteresis loop at relative pressures P/P_0 of 0.20–0.90. Type H3 hysteresis, according to the IUPAC classification, is associated with open and irregularly shaped pores, usually related to slit-like structures or flat plates rather than closed cavities. Another

characteristic is that the adsorption branch resembles a type II isotherm [48, 49].

From Fig. 1 (b), it is possible to observe that the ACP presents an isotherm type IV with an H2 hysteresis loop from 0.1 to 0.9 relative pressure, and can be classified as a mesoporous material according to IUPAC classification. The rapid increase in the adsorbed amount at low relative pressures ($P/P_0 < 0.2$) can be attributed to the filling of micropores and the formation of the N_2 monolayer. Additionally, in this region, an inflection point in the adsorption curve is observed, indicating the transition from micropore adsorption to the onset of capillary condensation in mesopores [50].

Table 1 summarizes the main features for activated carbons from lignocellulosic materials of literature works obtained by microwave irradiation, compared to ACM, and obtained by pyrolysis, compared to ACP. The BET surface area (S_{BET}) obtained for ACM was $88.116 \text{ m}^2 \text{ g}^{-1}$, the pore volume (V_p) was $0.080 \text{ cm}^3 \text{ g}^{-1}$ and the average pore width (D_p) was 3.819 nm. The characteristics presented in Table 1 corroborate the mesoporous character of the material obtained by microwave, with an average pore width ranging from greater than 2 nm to less than 50 nm. Gomez-Avilés et al. [51] reported a surface area of $44 \text{ m}^2 \text{ g}^{-1}$ for lignin-activated carbon, prepared using a 3:1 ratio of $\text{FeCl}_3 \cdot 6 \text{ H}_2\text{O}$ to lignin, at 800 W for 3 min within the inner chamber of a conventional microwave furnace with slight modifications. Before heating, a N_2 flow ($150 \text{ Ncm}^3 \text{ min}^{-1}$) was passed to ensure an inert atmosphere inside the flask. The authors conducted their study at various impregnation ratios and time intervals. For a 1:1 ratio, 800 W, and a 30-minute time, they obtained a surface area of $738 \text{ m}^2 \text{ g}^{-1}$. Zhou et al. [52] used corncob to develop activated carbon by microwave

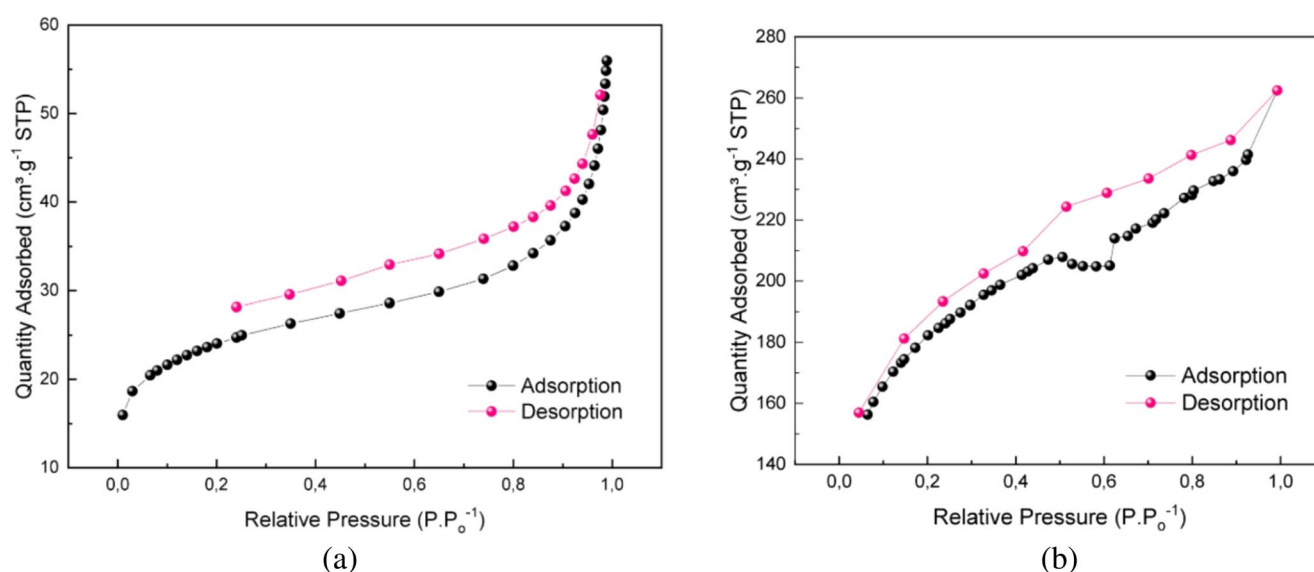


Fig. 1 N_2 adsorption-desorption isotherms of ACM (a) and ACP (b) samples

Table 1 Summary of the porous texture of ACM, ACP, and literature-activated carbons (AC)

Porous material (AC)	Time (min)	T (K)	S_{BET} ($\text{m}^2 \text{g}^{-1}$)	Reference
ACM	1.5*	-	88.116	Present study
Lignin	3*	-	44.0	[39]
Lignin	30*	-	738.0	[39]
Corncob	3*	-	1149.0	[52]
Corncob	7*	-	1405.0	[52]
Almond shell	15*	-	839.60	[38]
Cupuaçu shells waste	120*	-	863.0	[53]
Brazilian Nutshell waste	120*	-	840.0	[53]
ACP	120**	973	587.8	Present study
Açaí	90**	973	920.5	[34]
Murumuru endocarp	120**	723	271.18	[29]
Açaí	60**	1123	703	[45]
Brazil nut	60**	1123	911	[45]
Babassu	60**	1123	1101	[45]
Oil palm shell	60**	1123	569	[45]

*Time of microwave irradiation. **Time of pyrolysis

irradiation. The precursor material was impregnated with a 2:1 ratio of ZnCl_2 and KOH for two different materials. The mixture was magnetically stirred with 100 mL of the solution. The temperature was set at 85 °C, and the reaction was refluxed for 4 h. Afterwards, microwave-assisted activation was performed in a laboratory microwave oven at a frequency of 2.45 GHz. For the chemically activated carbon with ZnCl_2 , the operating conditions were 700 W for 3 min, and for the activated carbon with KOH, the conditions were 600 W for 7 min. The surface areas obtained were 1149 and 1405 $\text{m}^2 \text{g}^{-1}$, respectively. Du et al. [38] used an almond shell to obtain activated carbon by a microwave oven modified at a frequency of 2.45 GHz, with a mass ratio of 3:1 of ZnCl_2 and biomass, 900 W, and an activation time of 15 min under a $100 \text{ cm}^3 \text{ min}^{-1}$ nitrogen flow. The authors obtained a specific area of 839.60 $\text{m}^2 \text{g}^{-1}$. Cruz et al. [48] used Amazonian waste, such as cupuaçu shells and Brazil nut shells, as raw materials to obtain activated carbon. The biomass was mixed in an aqueous suspension of citric acid (1.5 mol L^{-1}) and placed in a reactor. The materials were hydrothermally carbonized using a laboratory microwave station operating at 2.45 GHz and 1600 W for 120 min. The system was heated to 200 °C. Afterwards, the samples were activated in a tubular furnace under a flow of 80 mL of $\text{CO}_2 \text{ min}^{-1}$ at 880 °C for 5 h. Values of 863.0 and 840.0 $\text{m}^2 \text{g}^{-1}$ were obtained for the specific surface area of the activated carbon from cupuaçu and Brazilian nut shells, respectively. Compared to biomass-activated carbons developed by microwave irradiation, the surface area obtained for Ucuuba activated carbon was not the highest. However, it demonstrates the potential for developing carbonaceous materials

through more accessible and simple methodologies. Evaluating the operational conditions of the works reported in the literature, with a methodology similar to that developed in the present study, the ACM presented satisfactory characteristics in an extremely short process time (90 s) without nitrogen flow, when compared to other materials by microwave and other methods such as pyrolysis, reducing the energy cost, making the production process simpler, reducing the steps and chemicals, considering that the adsorbent material is responsible for about 70% of the operational costs of processes such as adsorption [43, 44].

For ACP, the S_{BET} obtained was 587.5 $\text{m}^2 \text{g}^{-1}$. Boubli et al. [34] produced activated carbon from Açaí biomass. Chemical activation was performed using ZnCl_2 (1:1), and a pyrolysis step was conducted in a quartz tube under a N_2 atmosphere with a flow rate of 0.25 L min^{-1} , at a heating rate of $283.15 \text{ K min}^{-1}$ up to 973.15 K for 90 min. In their studies, they obtained a value of 920.5 $\text{m}^2 \text{g}^{-1}$ for the specific surface area. In the studies by Costa et al. [29], Murumuru waste was used to obtain activated carbon. The raw material was initially treated with NaOH (0.5 mol L^{-1}) for 6 h, with stirring every 30 min. The material was chemically activated with ZnCl_2 in a 1:2 ratio (biomass: ZnCl_2) at a temperature of 80 °C for 4 h. Subsequently, the material was oven-dried and then activated in a muffle furnace at 723 K for 2 h. The authors determined a specific surface area of 271.18 $\text{m}^2 \text{g}^{-1}$. Nobre et al. [45] studied different biomasses from the Amazon region to obtain activated carbon. All materials were pyrolyzed separately in a muffle furnace. The biomass was placed in the reactor and heated at a rate of 100 °C h^{-1} until 450 °C, and then maintained for 1 h. Physical activation was then performed. The carbons were heated to 1123 K and maintained for 60 min, using a CO_2 gas flow rate of 150 mL min^{-1} . The authors obtained specific surface areas of 703, 911, 1101, and 569 $\text{m}^2 \text{g}^{-1}$ for activated carbon from açaí, Brazil nut, babassu, and oil palm shell.

Using the XRD method, the structure of the biomass and the carbons produced were characterized. Figure 2 shows the X-ray diffraction patterns for the residue, ACM, and ACP. The peaks at $2\theta = 19.01^\circ$ and 23.64° in the diffractogram of the residue are characteristic of cellulose [52, 54]. After microwave carbonization and pyrolysis, the structure of cellulose is destroyed. Three peaks at $2\theta = 19.10$, 22.91 , and 23.69° are observed in the diffractogram of ACM, and two peaks at $2\theta = 24.89^\circ$ and 43.83° are observed in the diffractogram of ACP. Peaks in the region of $2\theta = 24^\circ$ may represent the diffraction of disordered carbon structures corresponding to the (002) plane. For both activated carbons (ACM and ACP), broad peaks were observed in the region of $2\theta = 24^\circ$; the weak intensity of the peaks in this region suggests a disordered graphite structure in the produced materials corresponding to the (1) plane [40, 52, 55]. The

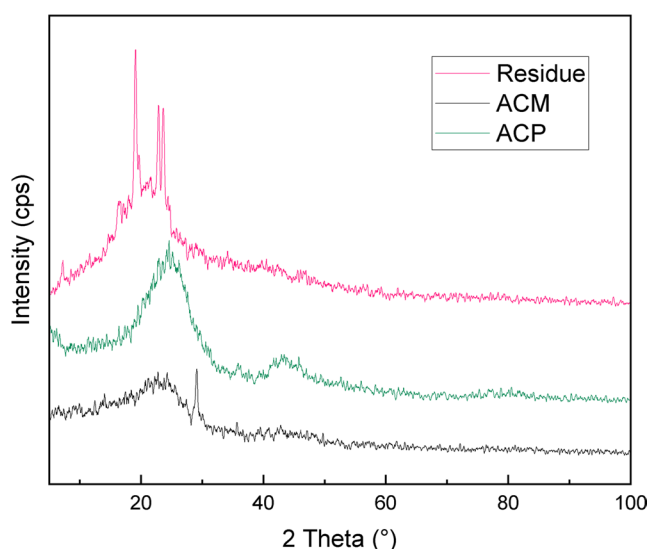


Fig. 2 X-ray diffractograms of Ucuuba, ACM, and ACP

broader diffraction peaks suggest the presence of amorphous carbon. In other studies, similar diffraction patterns have been observed for carbonaceous materials derived from biomass [40, 52, 54–56].

Figure 3 presents the FTIR analysis for the ucuuba residue, ACM, and ACP. A broad band at approximately 3440 cm^{-1} could be observed in all samples, which can be attributed to the O–H stretching vibration of the hydroxyl functional groups [38, 57]. The band at approximately 2956 cm^{-1} in residue was attributed to the C–H stretching vibration [38], which is not present in ACM and ACP. The band between 2917 and 2850 cm^{-1} in the residue corresponds to the C–H band of methyl and methylene groups present in cellulosic materials. The stretching vibrations at 1737 and 1643 cm^{-1}

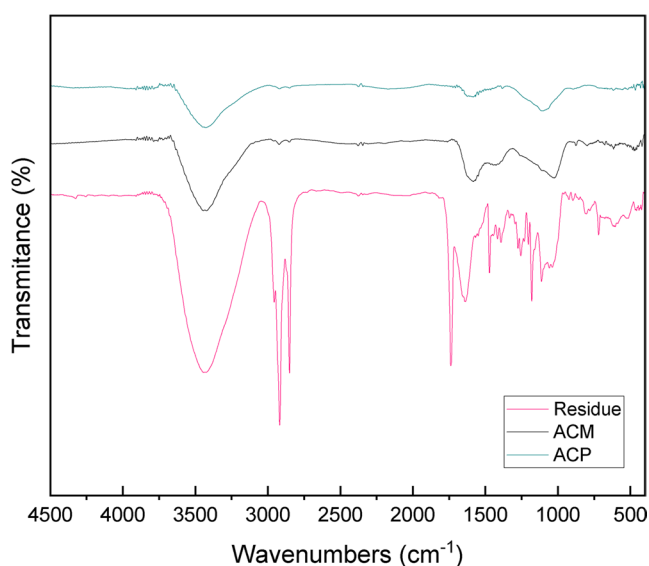


Fig. 3 FTIR vibrational spectra of Ucuuba, ACM, and ACP

can be attributed to the C=O group of ketones, aldehydes, lactones, or carboxyl groups [57]. Furthermore, the bands at approximately 1000 and 1259 cm^{-1} generally correspond to the stretching of oxidized carbons (C–O) in acids, alcohols, phenols, ethers, and ester groups [58, 59]. A series of bands were significantly reduced after carbonization of the residue in the range of 500 – 1790 cm^{-1} in ACM and ACP. This phenomenon is possibly due to the breaking of chemical bonds in the Residue [38].

Figure 4 shows the thermogravimetric and differential thermogravimetric (TG and DTG) curves for residue (a) and ACM (b). These curves demonstrate the thermal stability of the materials over a range of temperatures (21 – 800 °C). The TG and DTG curves for the Residue in Fig. 4(a) show three stages of mass loss. The first mass loss, approximately 6% of the initial weight, occurred between 21 and 168 °C and is attributed to moisture loss by the material [7, 57, 60]. The second mass loss, approximately 23%, occurred between 168 and 305 °C and was attributed to the decomposition of hemicellulose, as evidenced by a DTG peak at 282 °C . A third event occurs from 305 to 459 °C , with a peak on the DTG curve at 343 °C , accounting for approximately 41% of the mass loss and corresponding to the decomposition of cellulose and lignin [7, 57, 60]. Mass losses in the temperature range between 230 °C and 450 °C are mainly associated with the degradation of cellulose and hemicellulose, as they are thermally less stable than the lignin structure [7]. Lignin degradation begins at lower temperatures, similarly to hemicellulose, and persists up to approximately 600 °C . Thus, the waste observed at the end of the curve is attributed to lignin decomposition, due to its greater complexity and stability compared to the other components of the material [57]. Similar results were obtained by Queiroz et al. [60], Raupp et al. [57], and Thomaz et al. [7] for biomasses. In Fig. 4(b), mass losses are observed in temperature ranges similar to those identified in Fig. 4(a), though less significant. The intensity of the events in the DTG curve indicates a lower percentage of mass loss for ACM, with a less pronounced main decomposition peak, suggesting a smaller amount of volatile compounds and lignocellulosic residues in the sample due to the microwave thermal activation process. However, even after heat treatment, there is still plant residue present in ACM.

Figure 5 presents the micrographs for ucuuba waste (a), ACM (b), and ACP (c) before de adsorption. In Fig. 5(a), irregular and disordered structures typical of lignocellulosic wastes are visible. For ACM and ACP (Fig. 5(b) and (c) respectively), typical features of activated carbons can be observed, for example, agglomerated and disordered particles with some voids and cavities. The void fraction is favorable for adsorption purposes, allowing the entrance of the contaminant molecules inside the adsorbent.

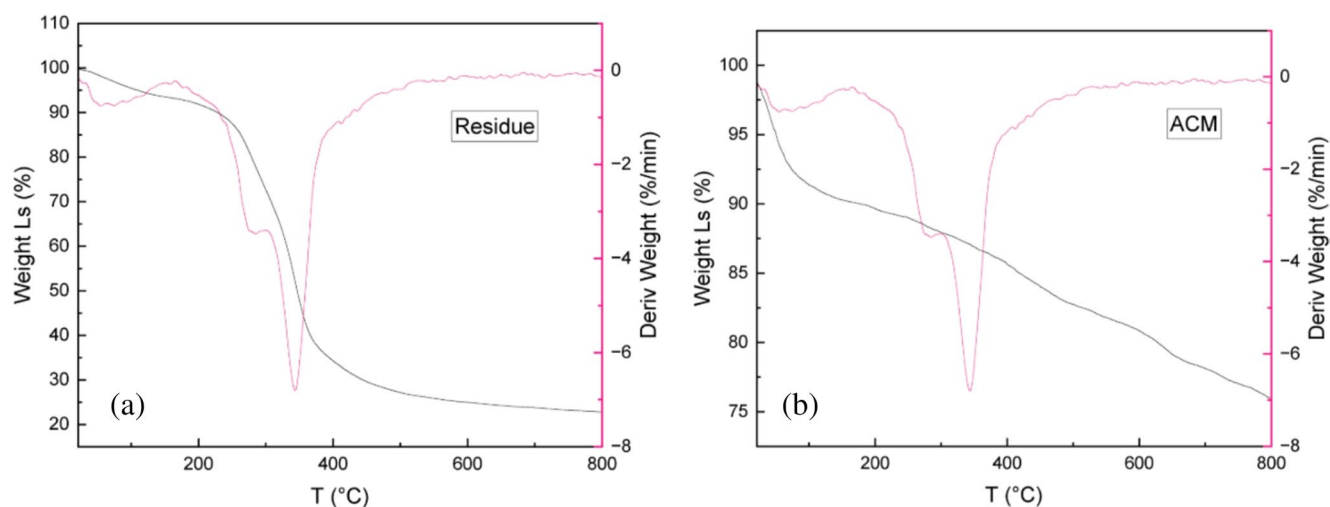


Fig. 4 TG and DTG curves of residue **(a)** and ACM **(b)**

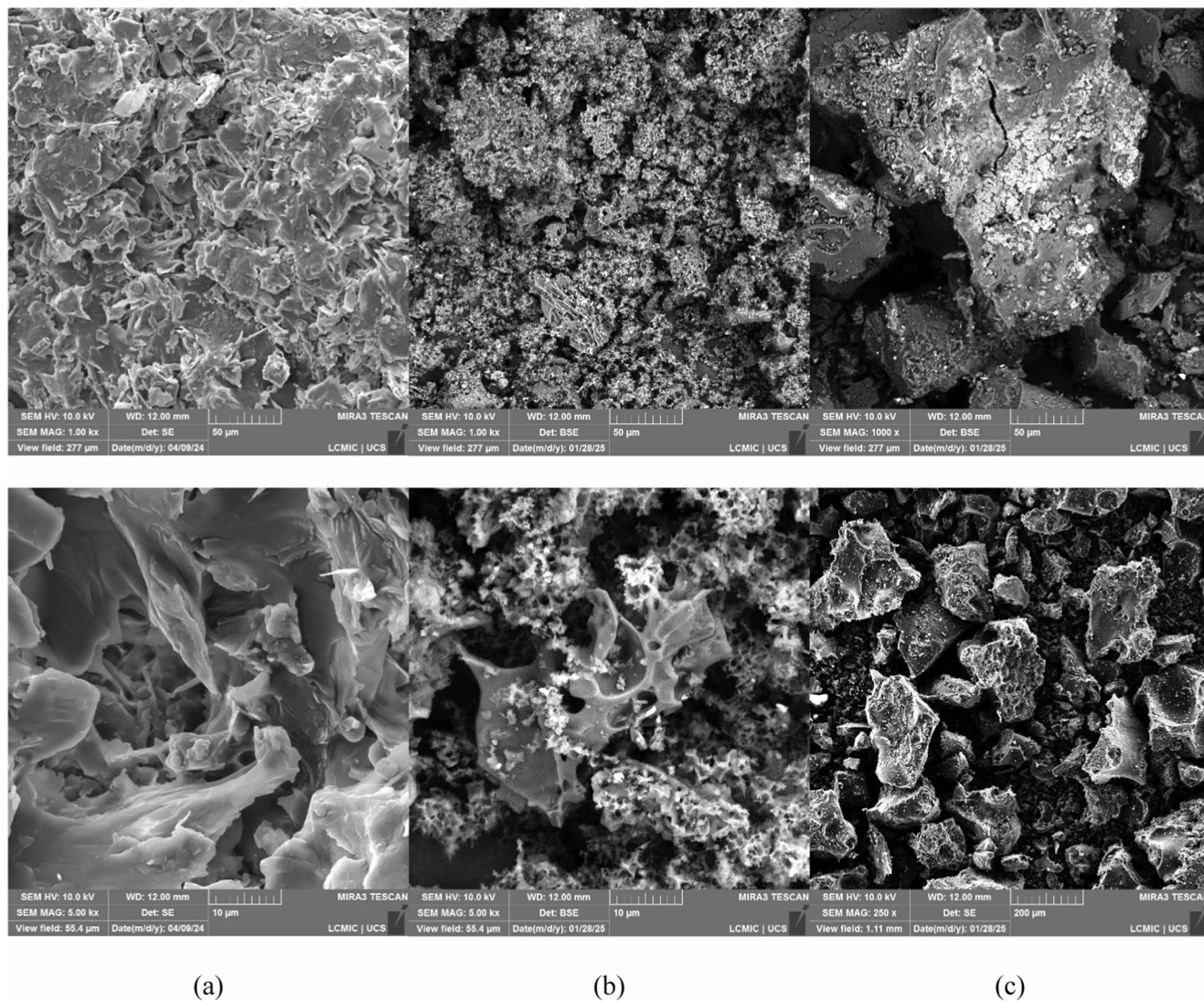


Fig. 5 SEM images: **(a)** ucuuba waste (1000× and 5000×), **(b)** ACM (1000× and 5000×), and **(c)** ACP (1000× and 250×)

The surface charge of the adsorbent material is of great importance in the adsorption process, and the pH of the working solution directly influences the surface charge of carbon-based materials [57, 61]. The pH_{PZC} analysis allows the prediction of the surface charge as a function of pH, determining the pH at which the surface charge of the material is zero [57]. Figures 6 (a) and (b) show the graphs for the pH_{PZC} of the prepared carbons, ACM and ACP, respectively. It was possible to determine that for ACM, the pH_{PZC} was 7.0, and for ACP, the pH_{PZC} was 5.77. Therefore, the activated carbons become positively charged in aqueous solutions with a pH lower than the pH_{PZC} ($\text{pH} < \text{pH}_{\text{PZC}}$), where the functional groups are protonated, which favors anionic adsorption. In aqueous solutions with a pH higher than pH_{PZC} ($\text{pH} > \text{pH}_{\text{PZC}}$), the activated carbons become negatively charged due to the deprotonation of functional groups on the surface of the materials, which favors cationic adsorption [47, 62–64].

3.2 pH effect on the dyes' adsorption

The amount of contaminant adsorbed by the adsorbent strongly depends on the pH of the solution. Therefore, studying the pH variation of the working solution facilitates understanding the ionization degree of the contaminant molecule and the functional groups on the surface of the adsorbent material, which causes changes in the adsorption capacity [65]. Figures 7 (a) and (b) show the effect of the initial pH of the solution on the adsorption capacity of the TY and MB dyes, respectively, by ACM and ACP. In Fig. 7 (a), it was found that for the TY dye, ACM showed a significant adsorption capacity only at pH 2, with a value of 18.73 mg g^{-1} and a removal efficiency of 44.72%. At pH

values greater than 2, the adsorption capacity and removal efficiency were zero. For ACP, the adsorption capacity values were higher when compared to those obtained for ACM. Figure 7 (a) shows an adsorption capacity of 31.48 mg g^{-1} and a removal efficiency of 81.23% at pH 2. It can be observed that with increasing pH, the adsorption capacity decreases, reaching 17.49 mg g^{-1} at pH 4 and 4.14 mg g^{-1} at pH 10. The decrease in the adsorption capacity of TY by ACM and ACP as pH increases is due to the rise in negative charges on the adsorbent surface, which reduces the positively charged sites and thus decreases the attraction of anionic dyes to the material's surface. This condition leads to electrostatic repulsion because it does not support the adsorption of anionic dyes such as TY [66]. From Fig. 7 (b), it was observed that for the MB dye, both ACM and ACP presented good adsorption capacity throughout the pH range studied. For ACM at pH 2, an adsorption capacity of 31.55 mg g^{-1} was obtained. This value increased to approximately 41.06 mg g^{-1} at pH 4, remained practically constant for all pH values above 2, and presented a removal efficiency of 98%. For ACP, the adsorption capacity remained constant across the entire pH range studied, yielding approximately 42 mg g^{-1} with 100% removal efficiency. From the results obtained, it was observed that the change in pH of the MB solution had no significant effect on the adsorptive process for the two carbons produced. In addition to MB being a cationic dye (positively charged), which tends to be attracted to negatively charged surfaces, the results suggest that other types of interaction occur between the surface of the material and the contaminant, such as physical interactions, independent of the pH. The subsequent studies were then carried out at a pH of 2 for TY and a pH of 6.5 for MB.

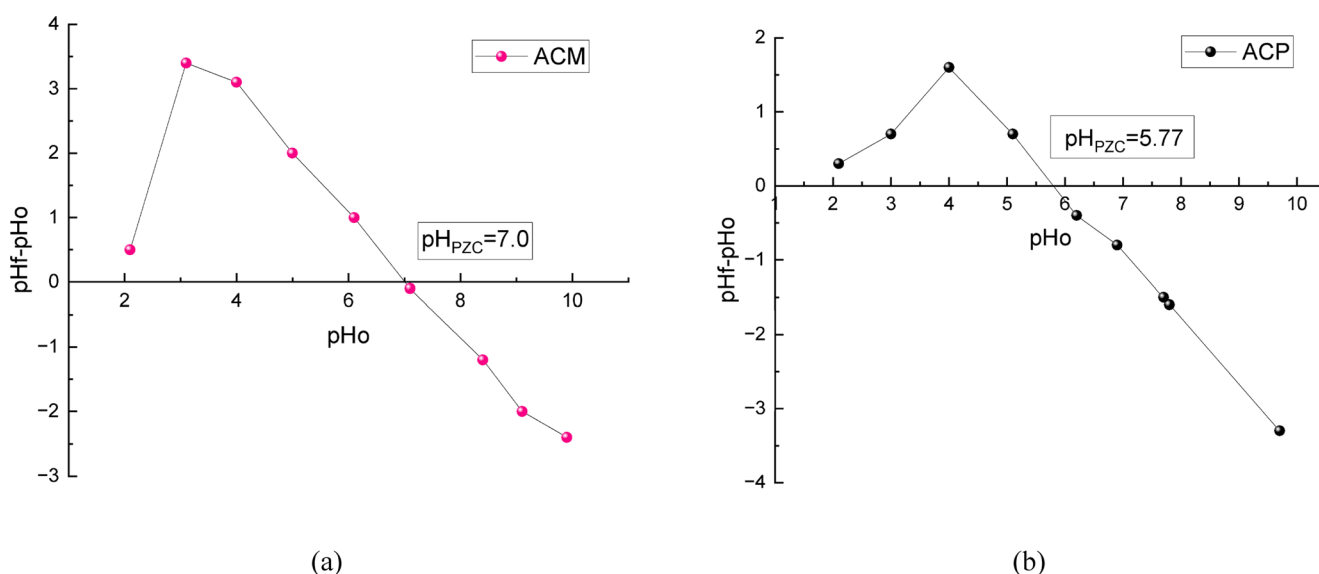


Fig. 6 pH_{PZC} of ACM (a) and ACP (b)

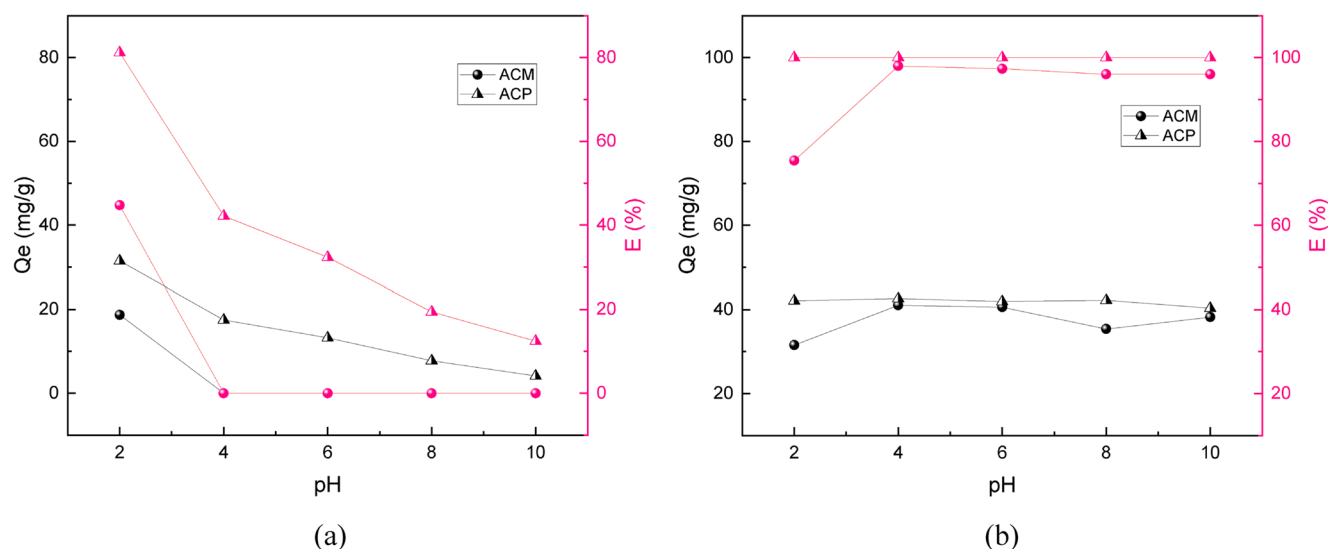


Fig. 7 pH effect on the adsorption of tartrazine yellow in 6(a) by ACM ($E=44,72\%$) and ACP ($E=81,23\%$), and adsorption of methylene blue in 6(b) by ACM ($E=98\%$) and ACP ($E=100\%$)

For comparison, comminuted Ucuuba (*Virola surinamensis*) waste (0.25 mm) was applied for TY and MB dyes adsorption, in the same experimental conditions as Fig. 7. A pH of 2 was used for TY, and a pH of 6.5 for MB. The removal percentage values were less than 12.4%. This result indicates that Ucuuba waste should be converted into carbonaceous materials for the adsorption of these dyes, as presented in this work.

3.3 Adsorption kinetics

The kinetic curves of TY adsorption on ACM and ACP, and MB on ACM and ACP are presented in Fig. 8 (a) and (b), respectively. The parameters obtained from the adjustment

of the data to the PFO, PSO, and Bangham mathematical models are shown in Table 2. From the kinetic study, it is possible to evaluate the mechanisms and the rate at which the adsorption process occurs. From Fig. 8 (a), it can be observed that for ACM, the process reached equilibrium quickly, in approximately 60 min, reaching the highest adsorption rates at the beginning of the experiment. In contrast, for ACP, equilibrium was reached in approximately 240 min. The values obtained for R^2 , R^2_{adj} and ARE for the TY molecule on both activated carbons indicated that the PSO model presented a better fit to the experimental data. The experimental value for the equilibrium adsorption capacity, q_2 , showed similarity with that obtained experimentally for ACM, while

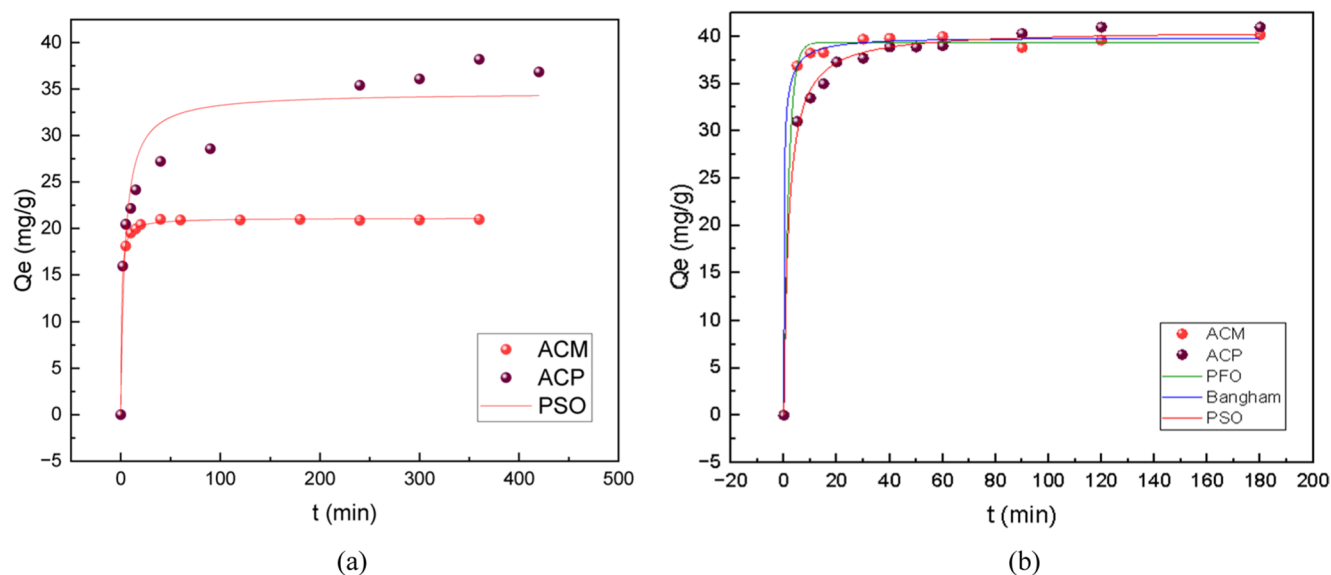


Fig. 8 Kinetic curves of the adsorption of tartrazine yellow on ACM and ACP in pH 2 (a) and methylene blue on ACM and ACP in natural pH (around 6.5) (b). Experimental data and fitting curves of the best kinetic model

Table 2 Kinetic parameters of Tartrazine yellow (TY) and Methylene Blue (MB) adsorption on ACM and ACP

Adsorbent	PFO		PSO		Bangham	
ACM - TY	q_e (mg g ⁻¹)	20.67	q_e (mg g ⁻¹)	21.07	q_e (mg g ⁻¹)	20.93
	k_1 (min ⁻¹)	0.396	k_2 (g min ⁻¹ mg ⁻¹)	0.059	k_B (min ⁻¹)	0.987
					n_B	0.986
	R^2	0.996	R^2	0.999	R^2	0.999
	R^2_{adj}	0.995	R^2_{adj}	0.999	R^2_{adj}	0.999
ACP - TY	ARE (%)	1.479	ARE (%)	0.445	ARE (%)	1.479
	q_e (mg g ⁻¹)	32.94	q_e (mg g ⁻¹)	34.62	q_e (mg g ⁻¹)	98.13
	k_1 (min ⁻¹)	0.154	k_2 (g min ⁻¹ mg ⁻¹)	0.007	k_B (min ⁻¹)	3.85×10^{-5}
					n_B	0.175
	R^2	0.834	R^2	0.919	R^2	0.993
ACM - MB	R^2_{adj}	0.815	R^2_{adj}	0.910	R^2_{adj}	0.991
	ARE (%)	15.880	ARE (%)	9.332	ARE (%)	15.880
	q_e (mg g ⁻¹)	39.37	q_e (mg g ⁻¹)	39.88	q_e (mg g ⁻¹)	39.79
	k_1 (min ⁻¹)	0.542	k_2 (g min ⁻¹ mg ⁻¹)	0.059	k_B (min ⁻¹)	4.493
					n_B	0.307
ACP - MB	R^2	0.997	R^2	0.998	R^2	0.998
	R^2_{adj}	0.997	R^2_{adj}	0.998	R^2_{adj}	0.998
	ARE (%)	1.315	ARE (%)	4.670	ARE (%)	1.315
	q_e (mg g ⁻¹)	38.77	q_e (mg g ⁻¹)	40.66	q_e (mg g ⁻¹)	41.85
	k_1 (min ⁻¹)	0.273	k_2 (g min ⁻¹ mg ⁻¹)	0.013	k_B (min ⁻¹)	0.507
					n_B	0.309
	R^2	0.973	R^2	0.995	R^2	0.998
	R^2_{adj}	0.970	R^2_{adj}	0.995	R^2_{adj}	0.998
	ARE (%)	2.719	ARE (%)	1.224	ARE (%)	3.847

for ACP, the adsorption capacity, q_2 . The results showed some discrepancy when compared to those obtained experimentally, not describing the behavior adequately. The good fit of the PSO model suggests that the adsorption process involves the sharing of electrons [66, 67]. In Fig. 8 (b), the adsorption equilibrium was reached quickly for ACM, approximately 60 min, and for ACP in 90 min. The values obtained for R^2 , R^2_{adj} and ARE for the MB molecule indicated that the PFO and Bangham model presented a good fit to the experimental data of ACM. The value obtained for q_1 and q_B of the models resemble those obtained experimentally for ACM. The good fit of the PFO model suggests that the process is mainly controlled by the mass transfer between the solution and the surface of the adsorbent, and does not consider more complex interactions. This trend corroborates the study on the effect of pH, which suggests that the strong interaction between the carbons and MB is not decisive for the process, indicating the predominance of physical interactions. This model is more adequate when the adsorption occurs quickly at the beginning, followed by an established equilibrium. The Bangham model suggests that the adsorption process is controlled by the diffusion of molecules within the pores of the adsorbent, not just by interaction at the surface.

Relating the results obtained from the mathematical models between the activated carbons and dyes, it was obtained that the high S_{BET} (587.38 m² g⁻¹) for ACP characterizes the predominant existence of mesopores and also the presence of micropores, as well as the presence of oxygenated functional groups observed in the FTIR, mainly bands associated with hydroxyls (–OH), carbonyls (C=O) and aromatic groups C=C, indicating a heterogeneous surface capable of promoting both electrostatic interactions and π – π interactions and hydrogen bonds. The pH_{PZC} of 5.77 reveals that, under conditions close to neutral, the ACP surface is predominantly negative, which favors the adsorption of cationic dyes and partially disfavors anionic dyes. In this sense, MB is a cationic dye with a planar aromatic structure, with a conjugated phenothiazine ring and ammonium groups that facilitate electrostatic attraction with the negative surface of the ACP. Furthermore, its high aromaticity allows strong π – π interactions with the graphitic domains of coal observed by XRD, which intensify adsorption and result in more favorable kinetic parameters, with an excellent fit to the PSO model. These results suggest that the process is dominated by chemical adsorption, which depends on the occupation of active sites and is consistent with the

pseudo-second-order model [68, 69]. However, TY is an anionic dye with an azoaromatic structure, containing sulfonate groups ($-\text{SO}_3^-$) that are strongly ionized in aqueous media. These groups confer high solubility and a negative charge to the dye, which generates electrostatic repulsion with the ACP surface at pH above the point of zero charge.

Furthermore, the tartrazine molecule is larger and more hydrophilic, which can hinder access to micropores and reduce the effective adsorption rate. These factors can explain the lower values obtained for adsorption capacity and adsorption rate when compared to the performance of MB. Thus, although the PSO model adequately describes both systems, indicating that the occupation of specific surface sites controls the process rate, the greater affinity of methylene blue reflects the decisive role of π - π and electrostatic interactions. The faster equilibrium reached (90 min) corroborates its stronger affinity. While the extended time for TY (240 min) reinforces that the kinetics are limited by intraparticle transport resistance and possibly charge repulsion and solvation effects, which delay penetration to the most active internal sites, resulting in slower kinetics and lower adsorption capacity [62, 70]. Kinetic analysis of adsorption on ACM showed that, in general, the PSO model described the experimental behavior well, indicating that the occupancy of active sites controls the process rate. However, for MB, the best fits were obtained with the PFO and Bangham models, suggesting that film transport and intraparticle diffusion play a predominant role in this material. ACM had a low surface area ($88 \text{ m}^2 \text{ g}^{-1}$) and a poorly developed structure, with a predominance of macropores, which reduces the number of active sites and limits chemisorption. This characteristic, combined with the neutral pH_{pzc} (7), causes the surface to have a charge close to neutrality, weakening electrostatic interactions with the cationic MB. Thus, MB adsorption occurs primarily through physical interactions, such as diffusion in larger pores and van der Waals forces, rather than specific chemical interactions. This trend explains the better fit to the PFO and Bangham models and the rapid equilibration within 60 min.

In contrast, for TY, the better fit to the PSO model indicates a greater contribution from surface chemical interactions. Although it is an anionic dye, its high polarity and the presence of sulfonate ($-\text{SO}_3^-$) and azo ($-\text{N}=\text{N}-$) groups favor the formation of hydrogen bonds and dipole-dipole interactions with hydroxyl ($-\text{OH}$) and carbonyl ($\text{C}=\text{O}$) groups identified in the FTIR, especially at pH close to neutrality, where some of these groups are protonated. The sulfonate group confers a strong anionic character and high solubility. At the same time, the azo bond extends the molecule's electronic conjugation, facilitating π - π and dipolar interactions with the aromatic domains of ACM. Even with a low specific area, these localized interactions make

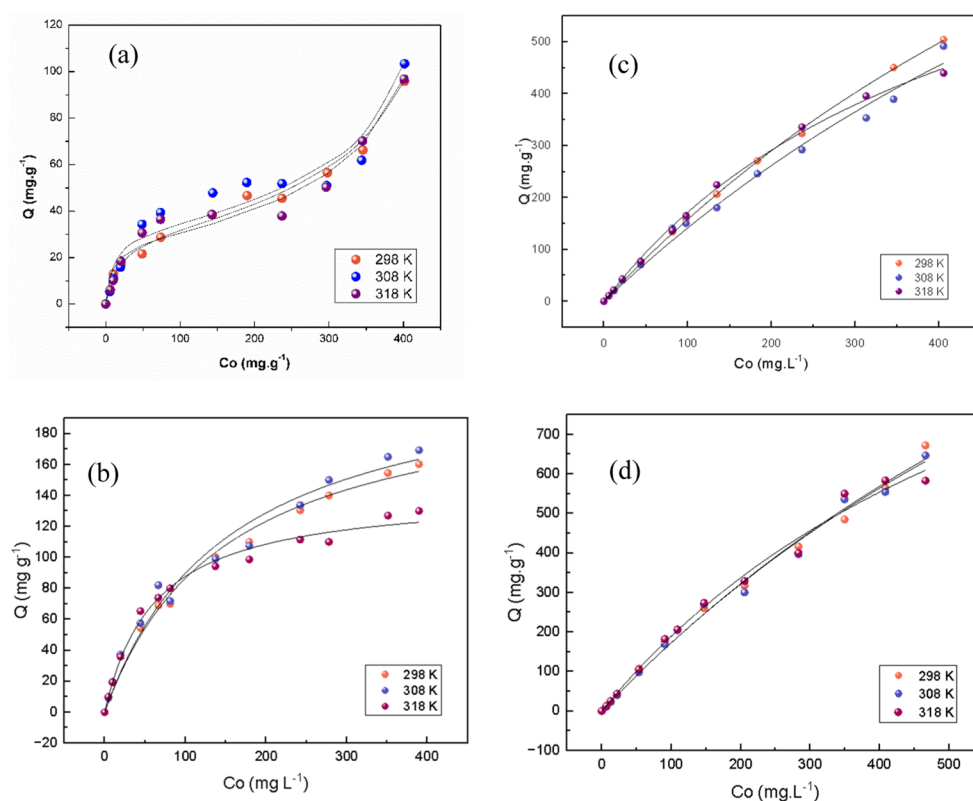
the adsorption mechanism more selective and chemically compatible with PSO. Thus, the distinct kinetic behavior between MB and TY reflects the interaction between the molecular structure of the dyes and the textural and chemical characteristics of ACM. MB, smaller, aromatic, and cationic, exhibits facilitated diffusion and adsorption governed by physical processes (PFO/Bangham), while TY, bulkier, anionic, and strongly solvated, interacts locally with polar groups, predominantly following PSO kinetics. Thus, although both reach equilibrium within 60 min, the nature of the molecular interactions is the determining factor for the predominant kinetic model in each case [62, 68–71].

3.4 Adsorption isotherms

Figure 9 shows the equilibrium isotherms obtained at temperatures of 298, 308, and 318 K for the adsorption of TY on ACM (a), TY on ACP (b), MB on ACM (c), and MB on ACP (d). The first observation is that, in general, temperature did not significantly affect the removal of TY and MB by ACM and ACP, nor did it enhance adsorption capacity. The second point is that the different systems presented different isotherm shapes. The system TY-ACM (Fig. 9(a)) presented a typical multilayer isotherm. Specifically, a favorable profile at equilibrium concentrations of 0 to 250 mg L^{-1} , attaining a plateau, relative to the first adsorption layer. However, at higher concentrations (250 to 400 mg L^{-1}), it exhibited an increase in adsorption capacity, not reaching saturation, and achieved a value of 103.58 mg g^{-1} at 35°C . In Fig. 9 (b), the isotherm profile is of the favorable type, suggesting that, even at low concentrations of the contaminant in the fluid phase, it is possible to obtain high values for adsorption capacity. The maximum adsorption capacity obtained was 169.32 mg g^{-1} at 35°C . In Figs. 9 (c) and (d), the isotherms showed a slight decrease in adsorption capacity with increasing temperature. In addition, the isotherms presented a concave profile, indicating a favorable behavior for the adsorption process of MB for ACM and ACP. The maximum experimental adsorption capacity obtained was 504.16 mg.g^{-1} for ACM and 671.99 mg.g^{-1} for ACP at 25°C . In these cases, it is clear that the plateau was not reached, indicating that the saturation was not attained in this concentration range.

The parameters of the isotherms estimated by the nonlinear regression methods are summarized in Table 3. Freundlich and Langmuir mathematical models fitted the experimental data well for MB adsorption for the two activated carbons and for TY-ACP. However, the systems with MB presented isotherms that do not reach the plateau, and consequently, the maximum adsorption capacity from the Langmuir model significantly overestimates the experimental values, resulting in a very high equilibrium concentration

Fig. 9 Equilibrium isotherms of tartrazine yellow on ACM (a) and ACP (b), and methylene blue on ACM (c) and ACP (d), adjusted to the Langmuir model



that exceeds the adsorption standards. Because of this, Freundlich is more suitable for systems with MB. For the system TY-ACP, the curves tend to a plateau, making Langmuir adequate, and the estimated q_m is close to the experimental values. Finally, for the system TY-ACM, the isotherms presented an unconventional shape, and consequently, the Langmuir and Freundlich models do not converge. Then, the BET model was the most adequate. The BET parameters were q_{BET} (from 26 to 31 mg g⁻¹), K_I (from 0.05 to 0.11 L mg⁻¹), and K_2 (kept in 0.002 L mg⁻¹).

The differences observed in the maximum adsorption capacities and isotherm shapes of the different systems corroborate the characterization results. ACP presented a significantly higher surface area (587.38 m² g⁻¹) compared to ACM (88 m² g⁻¹), with a predominance of micropores associated with the presence of mesopores. At the same time, ACM exhibited an essentially mesoporous structure with traces of macropores. This structural difference favored the diffusion and accumulation of dye molecules in ACP, resulting in higher maximum capacities (169.32 mg g⁻¹ for TY and 504.16 mg g⁻¹ for MB). Therefore, the superiority of ACP over ACM results from the combination of a larger surface area and the presence of micropores and active residual functional groups, which promote more efficient adsorption for both anionic and cationic dyes.

In contrast, the smaller area and predominance of macropores in ACM limited the number of available sites,

restricting its total capacity despite favorable surface interactions. The significant difference in available area, and especially in the presence of accessible micropores, in ACP allows it to accommodate many more molecules per unit mass. MB, due to its planar and relatively small nature, can accumulate densely in micropores and surfaces, generating very high q_m . Due to its structure, dissociation state, and solubility, TY does not exploit this large available area as efficiently. Thus, the strong electrostatic attraction for the MB cation enables a more efficient π - π interaction and a lower solvation effect, resulting in MB being adsorbed in much larger quantities than TY on both carbons, a difference that is especially pronounced in ACP due to its structural superiority [63, 64, 72, 73].

The results presented in Table 4 indicate significant differences in the adsorptive capacity of the materials tested in this study compared to literature data for the adsorption of TY and MB dyes. These data demonstrate that the activated carbons developed in this study—both those obtained by pyrolysis and those prepared by microwaves—have structural and chemical characteristics more favorable to adsorption, resulting in superior performance in the removal of anionic and cationic dyes.

The ΔG^0 values ranged from -24 to -13 kJ mol⁻¹ at all temperatures analyzed, confirming the spontaneity of adsorption [65, 79, 80]. Similar results were obtained by Tan et al. [79], who evaluated the adsorption of methylene

Table 3 Equilibrium parameters of TY and MB adsorption on ACM and ACP

System	TY – ACM			TY – ACP		
Temperature	298 K	308 K	318 K	298 K	308 K	318 K
Langmuir						
$q_{\max}$ (mg g ⁻¹)				214.77	228.01	142.21
K_L (L mg ⁻¹)				0.006	0.006	0.016
R^2	Not converge			0.990	0.979	0.990
R^2_{adj}				0.989	0.977	0.989
ARE (%)				10.22	12.49	3.60
AIC				47.25	58.51	41.69
$AIC_{Corrected}$				48.45	59.71	42.89
Freundlich						
$K ((\text{mg g}^{-1})(\text{mg L}^{-1})^{-1/n})$				7.51	7.56	12.53
N	Not converge			1.933	1.907	2.521
R^2				0.996	0.990	0.973
R^2_{adj}				0.996	0.989	0.971
ARE (%)				9.92	12.03	19.83
AIC				35.25	48.52	54.58
$AIC_{Corrected}$				36.45	49.72	55.78
		BET				
q_{BET} (mg g ⁻¹)	30.22	30.95	26.82			
K_1 (L mg ⁻¹)	0.05	0.10	0.11			
K_2 (L mg ⁻¹)	0.002	0.002	0.002			
R^2	0.989	0.932	0.967			
R^2_{adj}	0.989	0.931	0.966			
ARE (%)	8.50	27.28	22.64			
AIC	30.07	53.54	41.35			
$AIC_{Corrected}$	30.06	53.53	41.35			
System	MB – ACM			MB – ACP		
Temperature	298 K	308 K	318 K	298 K	308 K	318 K
Langmuir						
$q_{\max}$ (mg g ⁻¹)	1746.20	1710.95	947.70	2407.01	2302.44	1544.46
K_L (L mg ⁻¹)	9.96×10^{-4}	9.04×10^{-4}	0.002	7.73×10^{-4}	8.11×10^{-4}	0.001
R^2	0.999	0.990	0.998	0.994	0.993	0.991
R^2_{adj}	0.999	0.989	0.998	0.994	0.992	0.991
ARE (%)	2.798	7.964	7.280	5.792	5.564	5.040
AIC	34.16	74.25	44.00	76.78	79.35	81.26
$AIC_{Corrected}$	35.16	75.45	45.50	77.98	80.55	82.46
Freundlich						
$K_F ((\text{mg g}^{-1})(\text{mg L}^{-1})^{-1/n})$	3.47	3.21	5.76	3.86	3.77	5.50
n	1.203	1.208	1.368	1.200	1.197	1.298
R^2	0.999	0.993	0.991	0.996	0.994	0.989
R^2_{adj}	0.999	0.993	0.990	0.996	0.993	0.988
ARE (%)	7.35	7.496	17.834	9.331	14.010	17.22
AIC	38.49	69.66	62.45	70.44	77.79	84.38
$AIC_{Corrected}$	39.82	70.86	63.95	71.64	78.99	85.58

Table 4 Comparison of the adsorption capacities of different activated carbons (AC) for the removal of TY and MB

Adsorbent	Dye	q (mg g ⁻¹)	Reference
ACM	TY	103.58*	Present study
ACP	TY	169.32*	Present study
Iron-doped AC	TY	147.058	[63]
AC from boiler residue	TY	106.383	[74]
Corn cob nanobiochar	TY	85.47	[75]
AC from cassava sieve biomass	TY	20.83	[66]
Commercial granular AC	TY	10.204	[76]
ACM	MB	504.16*	Present study
ACP	MB	671.99*	Present study
AC from eucalyptus residue	MB	1000.00	[68]
AC from agricultural wastes	MB	398.19	[72]
AC from mango peels and seed wastes	MB	232.8	[69]
	MB	232.5	[77]
AC of <i>spathodea campanulata</i>	MB	86.207	[78]

*Maximum experimental adsorption capacity

blue on activated carbon prepared from coconut shells. Since the temperature effect was not clear, as shown in the equilibrium curves (Fig. 9), the ΔH^0 and ΔS^0 values were not estimated.

3.5 Desorption and reuse

The chemical desorption method was used, with 0.5 mol L⁻¹ NaOH as the eluent for tartrazine yellow and 0.5 mol L⁻¹ HCl for methylene blue. The results revealed that NaOH was efficient in the elution of TY, releasing more than 97.6% of the dye into the solution in 2 h. Besides, HCl was efficient in leaching MB from the loaded activated carbons with desorption percentages higher than 95%. These results prove the involvement of electrostatic interactions in the adsorption process.

Concerning the reuse, ACP could be reused 3 times, keeping the same adsorption capacity (MB around 670 mg g⁻¹, and TY around 170 mg g⁻¹), while ACM was reused 5 times with the same adsorption potential (MB around 500 mg g⁻¹, and TY around 100 mg g⁻¹). The lower potential for reuse of ACP can be explained by its more porous structure, which makes it difficult for the eluent (in desorption) and the dye solution (in adsorption) to access during consecutive cycles. However, in general, both materials demonstrated good performance suitable for more than one cycle.

3.6 Proposed adsorption mechanism

Based on the characterization results and adsorption experiments, a possible adsorption mechanism between the dye molecules and the activated carbons derived from ucuuba residue can be proposed. FTIR analysis indicated the

presence of oxygen-containing functional groups on the carbon surface, such as hydroxyl, carbonyl and carboxyl groups. These functional groups can undergo protonation or deprotonation depending on the solution pH, thereby influencing the surface charge of the adsorbent.

The strong influence of pH on the adsorption capacity observed for both dyes suggests that electrostatic interactions play an important role in the adsorption process. Under acidic conditions, the protonation of surface functional groups can generate positively charged sites that favor the adsorption of the anionic dye Tartrazine through electrostatic attraction. Conversely, under alkaline conditions, the deprotonation of surface groups produces negatively charged sites that enhance the adsorption of the cationic dye Azul de Metileno. The desorption experiments further support the participation of electrostatic interactions. Acidic solution (HCl) promoted the desorption of methylene blue, suggesting that protonation of the surface weakens the interaction between the positively charged dye molecules and the adsorbent. Similarly, alkaline solution favored the desorption of tartrazine, indicating that changes in surface charge can disrupt the electrostatic attraction responsible for dye adsorption. In addition to electrostatic interactions, other mechanisms may contribute to the adsorption process. The aromatic rings present in the dye molecules may interact with the graphitic domains of the carbon structure through π - π interactions. Hydrogen bonding between surface oxygenated groups and functional groups of the dyes may also occur. Furthermore, the porous structure of activated carbons facilitates adsorption through pore-filling mechanisms. Therefore, the adsorption process likely results from a combination of electrostatic interactions, π - π interactions, hydrogen bonding, and pore diffusion effects [81–83].

3.7 AC processing and performance

The activated carbon production route (conventional or microwave) directly influenced both its structural and surface properties, as well as its adsorption performance for the dyes studied. ACM presented a faster synthesis process and lower energy demands compared to conventional pyrolysis. Microwave activation promoted rapid and volumetric heating, reducing the total carbonization time and enabling the production of a material with a predominantly mesoporous structure, reduced surface area (88 m² g⁻¹), and the presence of macropores. This morphology favors the rapid diffusion of adsorbed molecules (fast kinetics). Still, it limits the total number of active sites, resulting in lower maximum adsorption capacities. However, precise control of the temperature and microwave power distribution is complex and can affect activation uniformity. This results in limited micropore formation and a smaller surface area, particularly when

the activating agent and exposure time are not optimized. ACP allowed greater control of the reaction temperature and atmosphere, favoring the development of a high surface area. However, it required a longer processing time, increased energy consumption, and the use of N_2 and HCl, all of which raise operational costs. However, it resulted in a material with a more ordered structure, a significantly larger surface area ($587.38 \text{ m}^2 \text{ g}^{-1}$), and a predominance of micropores combined with mesopores. This characteristic substantially increased the number of active sites, resulting in higher maximum adsorption capacities. The choice between the two materials, therefore, must consider the balance between adsorbent efficiency and production feasibility. Both materials produced here, ACP and ACM from Ucuuba (*Virola surinamensis*) wastes, demonstrated good adsorption potential and promote greater sustainability and benefits for the riverside cooperatives in Amazonia.

4 Conclusions

The production of activated carbon from Ucuuba by conventional and microwave pyrolysis processes proved to be efficient, ensuring attractive properties to the produced material. ACM presented an S_{BET} of $88.11 \text{ m}^2 \text{ g}^{-1}$ and a mesoporous pore size classification under simpler operating conditions, completed in less time, favoring a low energy cost. These properties ensured the potential for its use in the removal of MB with a maximum adsorption capacity of 504.16 and 103.58 mg g^{-1} for TY. For ACP, an S_{BET} of $587.38 \text{ m}^2 \text{ g}^{-1}$, and a predominance of micropores combined with mesopores was verified. The values obtained for the adsorption capacity were 169.32 mg g^{-1} for TY and 671.99 mg g^{-1} for MB adsorption. ACP could be reused 3 times, while ACM could be reused for 5 times, maintaining the same adsorption capacity. It was demonstrated that Ucuuba (*Virola surinamensis*) wastes can be transformed into efficient activated carbons by different techniques, fostering the sustainability of the riverside cooperatives in the Brazilian Amazonia.

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish All authors agree to publish this manuscript.

Competing interests Prof. Guilherme Luiz Dotto declares that he is Editor of Environmental Science and Pollution Research. The other authors declare that they have no competing interests.

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