



Eco-friendly removal of methylene blue from aqueous solutions using bark of *mimosa caesalpinifolia* from Northeast Brazil

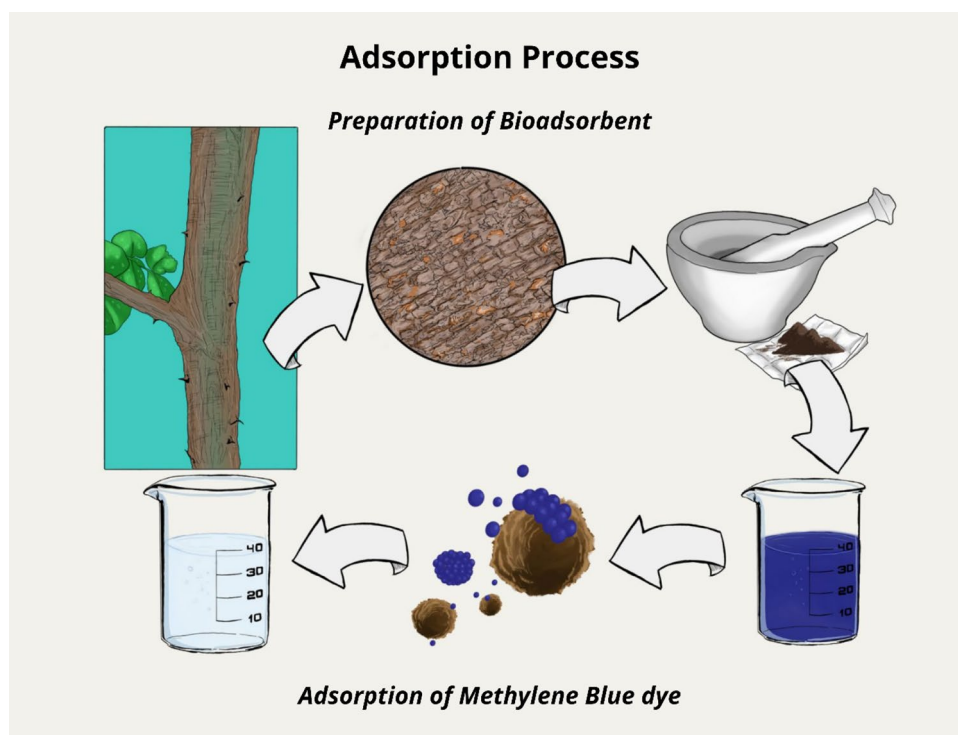
J. B. de Souza¹ · L. M. M. Ferreira¹ · L. D. Bessa¹ · R. A. da Silva Vieira¹ · R. López² · S. Khan^{1,3} · R. R. de Melo¹

Received: 24 February 2025 / Revised: 29 May 2025 / Accepted: 20 December 2025 / Published online: 12 January 2026
© The Author(s) 2026

Abstract

The research aims to use sabiá bark as a biosorbent for removing methylene blue dye from aqueous solutions. The sabiá bark was acquired from Fazenda Ipê, in the municipality of Governador Dix-Sept Rosado, in the state of Rio Grande do Norte, Brazil. It was crushed, macerated, and sieved for particle size standardization. The bark powder underwent extraction removal both hot and cold. The biosorbent was characterized using Scanning Electron Microscopy, Fourier Transform Infrared Spectroscopy, and Zero Charge Potential. Adsorption tests involving pH effects, kinetic studies, and isothermal studies were conducted. The results showed higher efficiency in alkaline medium. Equilibrium was reached in 60 min, and the Pseudo-2nd order kinetic model provided the best fit to the experimental data. Among the isothermal models, the Langmuir isotherm had the best fit at all three investigated temperatures, with 28 °C providing the best fit with a maximum adsorption capacity of 99.080 mg g⁻¹. Thus, the biosorbent from sabiá bark demonstrated promising results in removing methylene blue dye.

Graphical Abstract



Editorial responsibility: S. Mirkia.

Extended author information available on the last page of the article



Keywords Caatinga species · Textile dye · Effluent treatment · Reuse of non-timber residues · Textile industry

Introduction

The textile industry is responsible for boosting the economy and employing millions of people worldwide, allowing the application of dyes in the coloring of yarns, fibers, and fabrics (Manshoven et al. 2019). Despite this, the sector generates a large amount of colored wastewater containing toxic substances during this stage of production and when discharged without proper treatment, it can cause various environmental impacts and health problems for living beings (Behera et al., 2024). In light of this, contact with textile effluents can affect aquatic ecosystems, hindering the penetration of electromagnetic radiation in water during photosynthesis and causing harmful effects to species in their natural habitat (Moorthy et al. 2021). It can also cause cancer, allergies, and be mutagenic (Mashkoor; Nasar, 2020).

Among the cationic dyes used in the textile industry, methylene blue is the most commonly used. When wastewater containing this compound is discharged into water resources, it can significantly affect aquatic ecosystems and cause diseases in living organisms (Khan et al. 2022). It is worth mentioning that due to the diversity of substances present in textile effluents and the risks they pose to aquatic ecosystems and human health, it is unavoidable to implement effective treatment, as highlighted by Benkhaya, Rabet and Harfi (2020).

Many methods are applied to mitigate the harmful effects of these compounds in effluents. Among them, the following stand out: coagulation-flocculation (Chenna et al. 2022; Ihaddaden et al. 2022), photocatalysis (Subekti; Helmiyati, 2020), ozone oxidation (Quaff; Venkatesh; Venkatesh, 2021; Sharma; Chopra, 2022), electro-oxidation (Er; Gazigil; Yonar, 2024; Suman et al. 2023), hydrogen peroxide oxidation (Zawadzki; Deska, 2021), bioremediation (López-Miranda et al. 2020; Prabhakar; Gupta; Kaushik, 2022) and adsorption (Mirhosseini; Shamspur; Mostafavi, 2022; Sawalha et al. 2022). Out of the aforementioned techniques, the adsorption has attracted incredible attention from researchers for environmentally-friendly technologies (Solovyeva et al. 2021), as it is economical, easy to handle, and can be produced on a large scale (Wang et al. 2020). Among adsorbent materials used, activated carbon is commonly applied, as it has a high surface area (Bhattacharya 2023). However, the high financial cost associated with this adsorbent can make its use unfeasible (Mbarki et al. 2022). Thus, the search for low-cost materials with high adsorption capacity has become a critical challenge for researchers. An adequate research over the past decade demonstrated that

lignocellulosic materials have promising potential when applied as bioadsorbents for the removal of dyes in effluents (Alhashem et al. 2023; Ma et al. 2022). Among lignin and cellulose-based materials, residues from forest species are also being used for this purpose (Yang et al. 2022). Native species of the caatinga biome have been gaining attention in research, especially due to their great versatility in applications. Souza et al. (2018) highlight the use of native trees from the Caatinga in various sectors, emphasizing their application in furniture manufacturing and civil construction. Bark, wood chips, and sawdust are by-products of these types of industries (Top; Adanur; Oz, 2018). Consequently, the generation of wood waste from these activities is inevitable. Farias (2021) mentions that bark accounts for 10% of the solid waste from wood processing. One relevant issue is that bark has no applications compared to wood and is commonly discarded. Therefore, there is a search for sustainable alternatives for the repurposing of this by-product.

Among the environmentally friendly alternatives for the reutilization of solid waste, wood and non-wood by-products can be used for the treatment of wastewater generated during dyeing processes. In the literature, no studies utilize the bark of the species *Mimosa caesalpiniiifolia* for this purpose. In light of this, the research aims to apply the bark of *Mimosa caesalpiniiifolia* as a bioadsorbent for the removal of methylene blue dye in aqueous solution, emphasizing the importance of adding value to the bark of this species, as well as mitigating another environmental problem caused by the improper disposal of methylene blue dye in water resources.

The research was conducted between December 2023 and February 2024 at the Federal Rural University of the Semi-Arid Region (UFERSA), Mossoró campus, located in the state of Rio Grande do Norte (RN), Brazil (Latitude: 5°12'12.2"S, Longitude: 37°19'30.6"W).

Materials and methods

Reagent

The methylene blue dye, obtained from Dinâmica Química Contemporânea LTDA, has the following specifications: molecular formula $C_{16}H_{18}ClN_3S \cdot 3H_2O$, molecular weight of 373.90 g mol⁻¹, and analytical purity of 97%. Sodium chloride (NaCl), with analytical purity, was also purchased from Dinâmica Química Contemporânea LTDA. Hydrochloric acid (HCl, 37%) and sodium hydroxide (NaOH, 98%) were obtained from VETEC and ALFATEC, respectively.



Equipment

For the preparation of the bioadsorbent, a Willey-type knife mill, an ION vortex model VX-28, and a CEN-TAURO digital water bath were used. The bioadsorbent was characterized using a TESCAN scanning electron microscope, model VEGA 3, and Fourier transform infrared spectroscopy (FTIR) on the Vertex 70 spectrometer, with a spectral range of 4000 to 400 cm^{-1} . The solutions were stirred using the SOLAB SHAKER incubator model 222 and a Wagner-type stirrer TECNAL, model TE-160. pH measurements were made using the pH meter model 5000 and a magnetic stirrer with heating, model SL-95. The absorbances of the solutions were determined using the Agilent Cary 60 UV–Vis spectrophotometer.

Preparation of bioadsorbent

The bark of the species *Mimosa caesalpinifolia* was kindly provided by the Ipê farm, located in the municipality of Governador Dix-Sept Rosado, in the state of RN (latitude 5°30'02"S and longitude 37°25'34"W). The bark was then processed in a Willey-type knife mill to obtain a powder form. It was also macerated and sieved to a particle size of 420 μm for powder standardization.

Next, the *sabiá* bark was subjected to hot extractives removal, following the modified methodology employed by Lehr et al. (2021). This step involved adding 10 g of bioadsorbent to a 250 mL Erlenmeyer flask containing 100 mL of distilled water. After homogenization, the Erlenmeyer flask was placed in a water bath at a temperature between 90 and 100 °C for 3 h. At the end of this period, the glassware was removed from the water bath, and the bark was separated from the water by filtration.

Subsequently, the bark was subjected to the cold extraction removal process, following the methodology described by Lin et al. (2021) with modifications. The material was added to a sealed container containing 300 mL of distilled water and placed under constant agitation using a Wagner-type stirrer for 24 h. After this period, the water was replaced, and the plant material was agitated for another 24 h. This procedure was repeated for an additional 9 days.

Characterization

Scanning electron microscopy (SEM) was conducted to analyze the morphology of the bioadsorbent before and after the adsorption process. This analysis was performed using a scanning electron microscope. The samples were placed on the support and coated with a layer of gold. Images were

captured at magnifications of 500 $\times$ and 1500 $\times$ using a 10 kV electron beam.

Fourier-transform infrared spectroscopy (FTIR) was performed to determine the functional groups present on the surface of the bioadsorbent. This analysis was conducted over a range of 4000 to 400 cm^{-1} .

The Zero Charge Potential (ZCP) of the *sabiá* bark was determined following the methodology described by Nindjio et al. (2022). In this analysis, 0.150 g of the bioadsorbent was added in contact with 50 mL of a 0.01 mol L^{-1} NaCl solution at different initial pH values (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12) in 50 mL Falcon tubes. The pH values were adjusted by adding 1.0 mol/L HCl and 1.0 mol L^{-1} NaOH to the 0.01 mol L^{-1} NaCl solution and measured using a pH meter and a thermal stirrer.

The solutions in different pH ranges were placed under constant stirring with a Wagner type stirrer at room temperature for 24 h. After this period, the solutions were removed from the stirring and the final pH values were measured. Using the data obtained, a graph of ΔpH versus initial pH was plotted, and the Zero Charge Potential (ZPC) was determined.

Preparation of methylene blue solution

The stock solution of the dye was prepared by dissolving 0.0100 g of methylene blue in a 100 mL volumetric flask containing 100 mL of distilled water. Subsequently, dilutions were made to concentrations of 2 mg L^{-1} , 4 mg L^{-1} , 6 mg L^{-1} , 8 mg L^{-1} , 10 mg L^{-1} , and 12 mg L^{-1} . Then, the absorbance readings of each solution were taken using the UV–Vis spectrophotometer to obtain the analytical curve, correlating concentration and absorbance.

Effect of pH on the adsorption process

For this analysis, Methylene Blue (MB) solutions at 50 $\text{mg}\cdot\text{L}^{-1}$ were prepared at different pH ranges (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12). Using a pH meter and under constant agitation with a thermal stirrer, the pH adjustments were made by adding 1.0 mol L^{-1} HCl and 1.0 mol L^{-1} NaOH solutions to the dye solutions, as described by Nayak and Pal (2021). Subsequently, 0.100 g of the bioadsorbent was added in contact with 25 mL of the MB solution at the defined pH in a 50 mL Falcon tube, remaining under constant agitation at 10 rpm on a Wagner-type stirrer for 24 h. After this period, the Falcon tubes were removed from agitation, and 4 mL aliquots were taken from each solution, centrifuged in a CENTRIBIO model centrifuge for 5 min, and their absorbances were measured using a UV–Vis spectrophotometer at a wavelength of 663 nm.



Adsorption kinetics

The adsorption kinetics in the removal of MB from an aqueous solution were investigated by adding 50 mL of a 50 mg L⁻¹ dye solution to a 125 mL Erlenmeyer flask. The pH of the solution was previously adjusted according to the parameters determined in the study of the pH effect. Subsequently, 0.2 g of the bioadsorbent was added in contact with the MB solution. At different time intervals (0, 5, 10, 15, 30, 60, 90, 120, 180, 240, and 300 min), the solutions were kept under constant agitation at 180 rpm and a constant temperature of 30 °C, controlled with the help of a SHAKER incubator, model 222 SOLAB. At the end of each specified time, the Erlenmeyer flasks were removed from agitation, centrifuged for 5 min, and 4 mL aliquots were taken for analysis using the UV–Vis spectrophotometer at a wavelength of 663 nm.

The amount of MB adsorbed at different time intervals was determined according to Eq. 1.

$$qt = \frac{(C_i - C_t)V}{m} \quad (1)$$

where qt is the amount adsorbed (mg·g⁻¹); C_i is the initial concentration of the dye (mg L⁻¹); C_t is the residual concentration of the dye after the completion of each time interval (mg L⁻¹); m is the mass of the bioadsorbent (g); and V is the volume (L) (Rego Junior et al., 2023).

The Pseudo-1st order, Pseudo-2nd order, intraparticle diffusion, Elovich, and Avrami kinetic models were fitted to the experimental data to describe the adsorption mechanisms, as highlighted in Table 1 in Eqs. 2, 3, 4, 5, and 6, respectively.

Adsorption isotherms

For the isotherm study, 0.1 g of the bioadsorbent was placed in contact with 25 mL of the MB solution at different concentrations (25, 50, 100, 200, 300, 400, and 500 mg L⁻¹) in 125 mL Erlenmeyer flasks. Subsequently, the solutions were placed under constant agitation at 180 rpm for 60 min in the SHAKER incubator. After the time elapsed, the Erlenmeyer flasks were removed from the incubator, the solutions were centrifuged for 5 min, and 4 mL aliquots were taken for absorbance readings using the UV–Vis spectrophotometer at a wavelength of 663 nm. The conditions for this analysis, such as equilibrium time and pH, were predetermined in previous studies.

The amount of MB adsorbed at different concentrations was calculated according to Eq. 7.

$$qe = \frac{(C_i - C_e)V}{m} \quad (7)$$

where qe is the amount adsorbed (mg g⁻¹) of the bioadsorbent as a function of time; C_i is the initial concentration at equilibrium (mg L⁻¹) of the dye solution, and C_e is the final concentration (mg L⁻¹) after the agitation time; m is the mass (g) of the bioadsorbent; and V is the volume (L) of the methylene blue solution (Rego Junior et al., 2023).

The Langmuir and Freundlich isotherms were the mathematical models fitted to the experimental data to describe the adsorption mechanisms in this study. The fittings are based on Eqs. 8 and 9, respectively.

$$q = \frac{q_{\max} K_L C_e}{1 + K_L C_e} \quad (8)$$

where q is the amount adsorbed (mg g⁻¹), $q_{\max}$ is the maximum adsorption capacity (mg g⁻¹), C_e is the residual

Table 1 Different adsorption kinetic models and their equations

Model kinetic	Equation	Observation	References
Pseudo-1st order	$\frac{dq_t}{dt} = K_1(q_e - q_t)$	K_1 =adsorption rate constant (min) q_e =adsorbed amount (mg·g ⁻¹) q_t =adsorbed amount in time (mg·g ⁻¹)	Teshager, Habtu e Mequanint, 2024
Pseudo-2st order	$\frac{dq_t}{dt} = K_2(q_e - q_t)^2$	K_2 =adsorption rate constant (min) q_e =adsorbed amount (mg·g ⁻¹) q_t =adsorbed amount in time (mg·g ⁻¹)	Teshager, Habtu e Mequanint, 2024
Intraparticle Diffusion	$qt = R_{id}\sqrt{t}$	R_{id} = model constant (g/mg.min-1/2) t =contact time (min)# α =inicial adsorption rate mg·g.min ⁻¹	Webber Morris, 1963
Elovich	$\frac{dq_t}{dt} = \alpha \exp(-\beta q_t)$	β =constante de desorção (mg·g ⁻¹) q_t =adsorvid amount (mg·g ⁻¹)	Aksakal e Ucin, 2010
Avrami	$\frac{dq}{dt} = 1 - \exp(-K_{AV}t)^n$	K_{AV} = constante cinética do modelo (min) n =ordem fracionária do processo t =tempo de contato (min)	Aslan, Aslan e İlhan, 2023



concentration at equilibrium (mg L^{-1}), and K_L is the Langmuir constant (L mg^{-1}) (Thongprasong; Thananant, 2022).

$$q = K_F C_e^{\frac{1}{n}} \quad (9)$$

where q is the amount adsorbed (mg g^{-1}), K_F is the Freundlich adsorption capacity constant, C_e is the residual concentration at equilibrium (mg L^{-1}), and $\frac{1}{n}$ is the surface heterogeneity constant ($\text{L} \cdot \text{mg}^{-1}$) (Thongprasong; Thananant, 2022).

Statistical analysis

The corrected Akaike information criterion (AICc) was developed by the Japanese statistician Hirotugu Akaike in 1978 and is used as a statistical analysis to determine which mathematical model is most likely to describe the experimentally obtained data, considering the maximum likelihood of the parameters (Akaike, 1979). Thus, the most suitable model will be the one with the lowest AICc value. The AICc is determined by Eq. 10.

$$AIC_C = \left[\frac{2K(K+1)}{n-k-1} \right] \quad (10)$$

where k is the number of parameters in the mathematical model and n is the number of observations.

The coefficient of determination (R^2) was also used to fit the kinetic and isothermal mathematical models to the experimental data, determining which model had the highest value of this parameter.

The software Microsoft Excel, Origin Pro Graphing & Analysis, and ImageJ software were used for the analysis of the experimental data.

Results and discussion

Scanning electron microscopy

Figure 1 highlights the micrographs of the bioadsorbent derived from the bark of the sabiá species before and after the adsorption processes of the MB dye. This allows for the observation of the porosity of the bioadsorbent's surface, which is essential for investigating the adsorption capacity of the material.

Figure 1.A displays the micrograph of the sabiá bark before the adsorption process, highlighting the pores, their size, and their arrangement on the surface of the bioadsorbent. Through analysis using ImageJ software, it was possible to approximately estimate the pore diameters, providing insight into the morphological characteristics of the adsorbent material. As a result, it is observed that the surface of

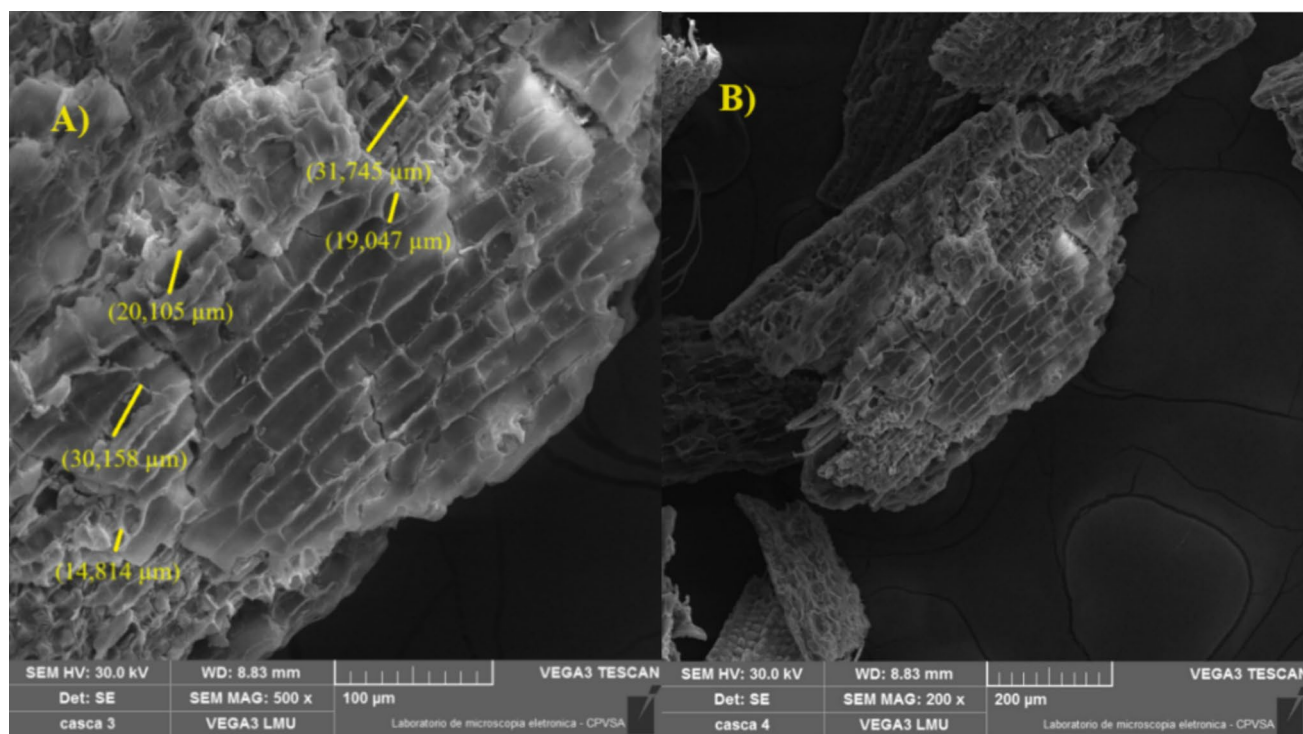


Fig. 1 Micrographs of the bioadsorbent a) before and b) after the adsorption process of the AM dye, with magnifications of 500 and 200 times, respectively



the bioadsorbent contains pores with diameters ranging from 14.814 to 31.745 μm .

In their recent study, Ma et al. (2022) highlight the use of scanning electron microscopy (SEM) for the morphological characterization of bioadsorbent derived from sunflower stalks, emphasizing the porosity of the lignocellulosic material with pores having a diameter of 1.34 nm. In the micrograph shown in Fig. 1b, a noticeable smoothing of the pores is observed following the adsorption of the methylene blue dye, which may be attributed to the occupation of active sites by dye molecules. A similar morphological alteration was reported by Yadav et al. (2022), indicating that dye adsorption can lead to a partial filling or coverage of surface pores.

Fourier transform infrared spectroscopy (ftir)

The FTIR technique is applied for the qualitative identification of the functional groups present on the surface of materials (Guerrero-Pérez; Patience, 2020). Figure 2 shows the infrared spectrum of the bioadsorbent before and after the adsorption process.

As highlighted in Fig. 2.1, the first absorption band, located between 3500 cm^{-1} and 3250 cm^{-1} , is characteristic of the hydroxyl functional group ($-\text{OH}$). The second band, found between 3000 cm^{-1} and 2700 cm^{-1} , is related to alkanes ($\text{C}-\text{H}$) stretching. The third peak, with a wavelength between 1750 cm^{-1} and 1500 cm^{-1} , indicates the presence of carboxylic acid groups ($\text{C}=\text{O}$). The fourth peak, with a wavelength between 1725 cm^{-1} and 1500 cm^{-1} , corresponds to aromatic rings ($\text{C}=\text{C}$). The fifth absorption peak is associated with alcohols ($\text{C}-\text{O}$).

Mandale et al. (2024) investigated the application of powdered Arjuna seeds as a lignin and cellulose-based bioadsorbent for the removal of malachite green dye. In the analysis of the infrared spectrum, the authors highlight the presence of oxygen and carbon in the bioadsorbent and the importance of these elements in facilitating the retention of adsorbate molecules in the pores of the adsorbent. Akkoz e Coskun (2023) emphasize the presence of OH , $\text{C}-\text{C}$, and $\text{C}-\text{OH}$ bonds in the spectrum of the bioadsorbent prepared from natural hemp fiber, noting that these functional groups are characteristic of cellulose, hemicellulose, and lignin.

As observed in Fig. 2.2, the adsorption of MB dye by the sabiá bark resulted in a significant intensification of the peaks of functional groups compared to the spectrum of the bioadsorbent before the adsorption process, especially in the fifth peak corresponding to $\text{C}-\text{O}$. In this regard, a recent previous study suggests that this phenomenon may be attributed to the formation of chemical bonds between the adsorbent and the adsorbate (Zhang et al. 2022).

Zero charge potential—ZCP

The Zero Charge Potential (ZCP) is used to investigate the surface charge of the bioadsorbent, determining the pH at which the sum of the surface charges of the material is zero (Sahu et al. 2020). In this analysis, if the solution's pH is higher than the pH at the Zero Charge Potential (pH_{PZC}), the surface charge of the adsorbent will be negative. However, if the solution's pH is lower than the pH_{PZC} , the surface charge of the adsorbent will be positively charged (Mbarki et al. 2022). Figure 3 shows the curve for

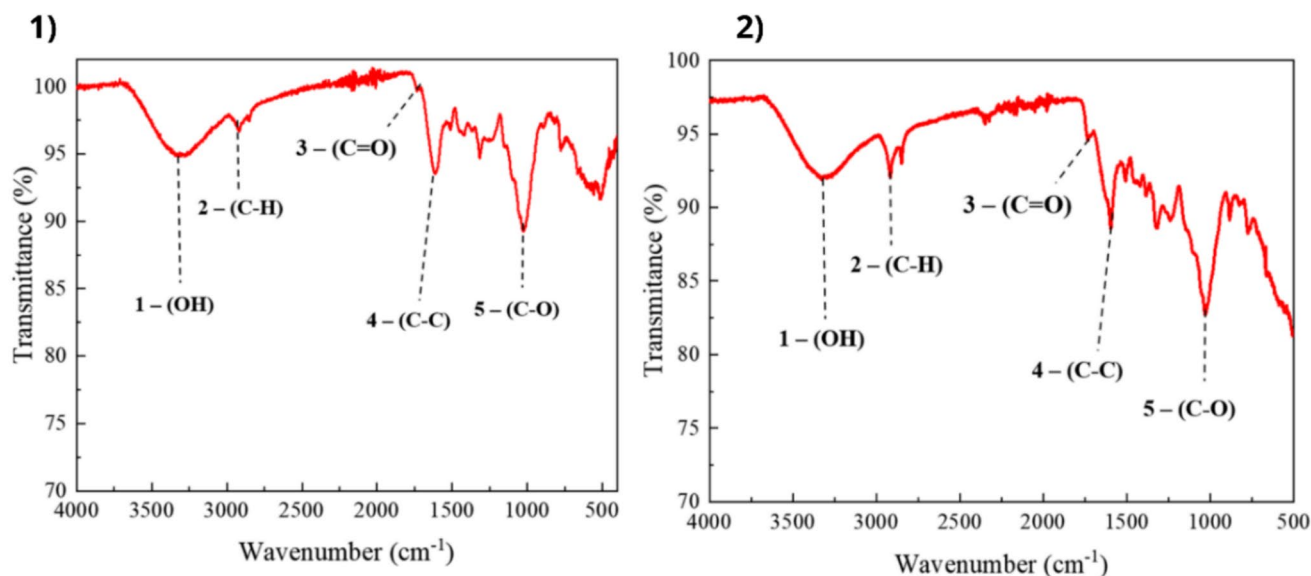


Fig. 2 Infrared spectrum of the bioadsorbent 1) before and 2) after the adsorption process, in the scanning range from 4000 to 500 cm^{-1}



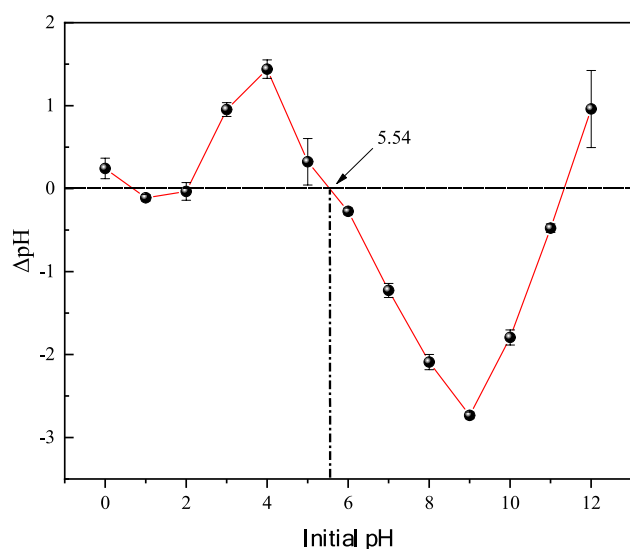


Fig. 3 Determination of the Point of Zero Charge of the adsorbent derived from sabiá bark, within a pH range from 0 to 12

determining the pH at the Zero Charge Potential (pHPZC) of the bioadsorbent.

As observed in the PCZ curve graph, the pH at the pHPZC for the sabiá bark is 5.54. Therefore, the arithmetic mean of these highlighted points is equivalent to the pHPZC of the bioadsorbent, which is 5.54 for the sabiá bark. Thus, if the pH of the solution is higher than the pHPZC, the sum of the surface charges of the bioadsorbent is negative, favoring the adsorption of cationic dyes. Conversely, if the pH of the solution is lower than the pHPZC, it indicates that the sum of the surface charges of the bioadsorbent is positive, favoring the removal of anionic dyes.

In the literature, other studies have analyzed the pHPZC of lignin- and cellulose-based bioadsorbents for the removal of cationic dyes: mangosteen peel powder with pHPZC of 4.9 (Phawachalotorn e Suwanpayak, 2021) and atemoya peel powder with pHPZC of 5.2 (Venceslau et al., 2021).

Effect of pH

pH is a factor that influences the adsorption process (Vojnovic et al., 2022), and therefore, it should be investigated. According to Fig. 4 highlighted below, it can be affirmed that the adsorption of the MB dye by the action of the sabiá bark is affected by pH, with more efficient removal observed at more alkaline pH levels compared to the initial pH values. The pH levels of 0, 1, and 2 had the lowest adsorbed quantities, measuring 10.992, 10.875, and 12.007 mg g⁻¹, respectively. Additionally, from pH 4 to 12, the adsorbed quantity remains constant, showing no significant changes.

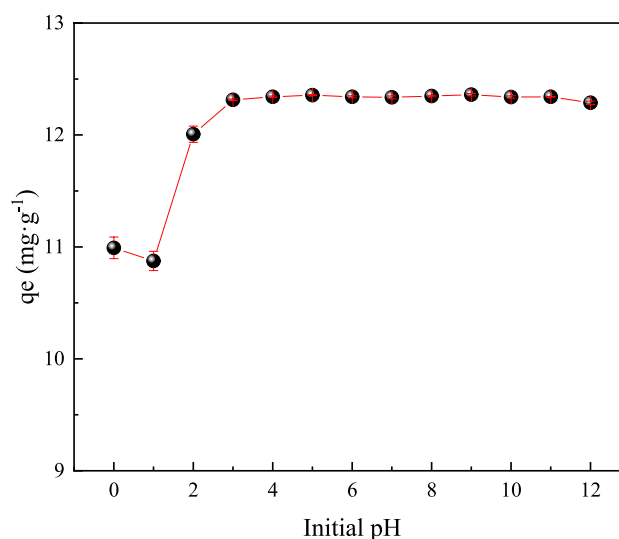


Fig. 4 Effect of the pH of the bioadsorbent with basic treatment on the adsorption of methylene blue dye within a pH range of 0 to 12

The MB dye is cationic, and adsorption will be more efficient in solutions with a pH above the zero charge point (pHPZC). As previously mentioned, the pHPZC of the bioadsorbent is 5.54. For better efficiency in the adsorption process, the pH of the MB dye solution must be above this value. In the literature, other studies have adjusted the pH of dye solutions to values above the pHPZC of lignin and cellulose-based bioadsorbents.

In their recent study, Giraldo et al. (2022) developed a bioadsorbent derived from orange peel waste for the removal of MB dye in aqueous solution. In this study, the authors determined the pHPZC of the bioadsorbent to be 3.5 and used an ideal pH of 7 for the dye solution, which is above the pHPZC value, thus favoring the removal of the cationic dye. Therefore, for the upcoming analyses in this study, the pH of the MB solution will be adjusted to approximately 7.

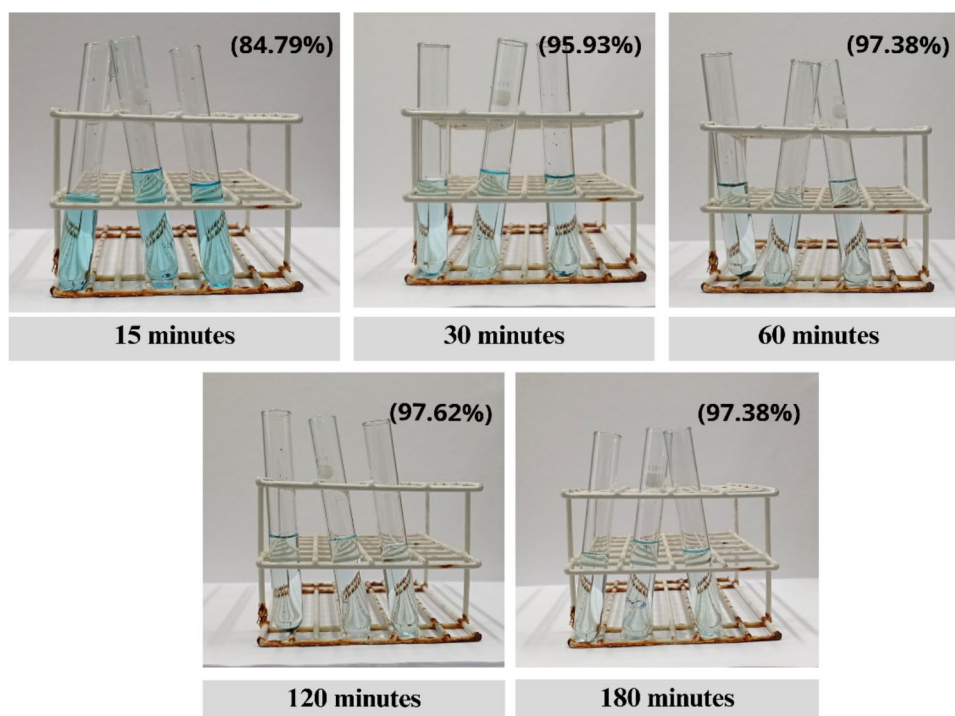
Adsorption kinetics

The kinetic study plays an important role in determining fundamental parameters in the adsorption process, providing the equilibrium time between the adsorbent and adsorbate, the rate of adsorption over time, and the predominant adsorption mechanism (Worch, 2021). Figure 5 highlights the adsorption process of the MB solution by the bioadsorbent after different contact times. The highlighted contact times are 15, 30, 60, 90, and 120 min, and it is noted that the longer the agitation time of the solution, the lower the intensity of the MB solution's color. In addition, the percentage of dye removal at each contact time interval is highlighted.

To analyze the fitting of kinetic models to the data obtained experimentally, the following parameters will be



Fig. 5 The MB solution after the adsorption process by the action of the bioadsorbent at different agitation times



used: corrected Akaike criterion (AICc), Akaike weight (w_i), and correlation coefficient (R^2). The values of the adsorption kinetics are highlighted in Table 2.

As presented in Table 2, it can be observed that the pseudo-second order model has the lowest AICc value (-23.517), the highest w_i (0.972), and R^2 (0.966), making it the model with the highest probability of describing the experimental data among the compared models in this analysis. Therefore, the pseudo-second order assumes that the rate-controlling step of the adsorption process is the chemical reaction that occurs between the liquid and solid interfaces (Simonin 2016). Figure 6 presents the comparison of the experimental data with the fit of the selected model.

As evidenced in Fig. 6, the equilibrium time of the bioadsorbent in the adsorption of MB was determined

to be 60 min, with no significant variations observed in the amount adsorbed as the agitation time increased. In this context, Hubbe et al. (2019) highlight that when the contact time between the adsorbent and adsorbate can be reduced without compromising removal efficiency, it represents an advantage for large-scale applications, as it allows for the optimization of industrial processes in dye removal.

The maximum adsorption amount of the pseudo-second-order model was 12.494 mg g^{-1} , which is in agreement with the experimentally obtained amount of 12.243 mg g^{-1} . Furthermore, the rate constant of the pseudo-second-order kinetic model was 0.034 g/mg min , reflecting the rate of the chemisorption process, as highlighted by Simonin (2016).

Table 2 Comparison of kinetic models in the adsorption of methylene blue dye by the action of sabiá bark based on the Akaike criterion

Model Kinetics	Parameters of model	Selection criteria				
		R^2	R^2_{aj}	AIC	AIC _C	w_i
Pseudo-1st order	$q_1 = 12.096$ $K_1 = 0.205$	0.929	0.908	17.939	16.225	0.025
Pseudo-2 nd order	$q_2 = 12.494$ $K_2 = 0.034$	0.966	0.956	25,231	23.517	0.972*
Difusão intrapartícula	$K_{id} = 0.177$ $C = 9.880$	0.512	0.373	1.299	3.014	0.000
Elovich	$a = 24,903.199$ $b = 1.250$	0.737	0.662	-4,882	-3,168	0,000
Avrami	$q_e = 12.096$ $K_{AV} = 0.453$ $n = 0.453$	0.929	0.893	15.939	11.939	0.003



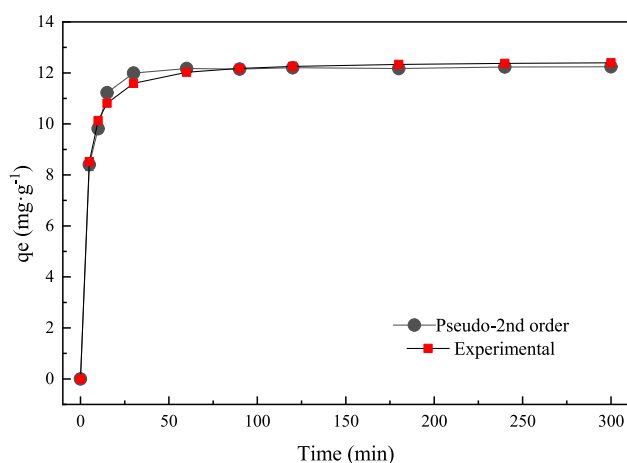


Fig. 6 Comparison of the fit of the pseudo-second-order kinetic model with the experimental data in the adsorption of methylene blue

Adsorption isotherms

The statistical parameters used (AICC, w_i , and R^2) to select the model with the highest probability of representing the experimental data for the removal of MB dye in aqueous solution by the action of the sabiá bark are presented in Table 3.

According to the parameters presented in Table 3, the Langmuir isotherm (28 °C) has the lowest corrected Akaike

Table 3 Comparison of the isothermal models for the removal of methylene blue by the action of the adsorbent derived from sabiá using the Akaike criterion

Models isotherm	Parametres of model	Temperature (°C)		
		28	38	48
Langmuir	$q_{\max}(\text{mg/g})$	99.080	99.015	101.447
	$K_L (\text{L/mg})$	0.082	0.112	0.101
	DPR	16.146	29.500	41.841
	R^2	0.989	0.981	0.974
	R^2_{aj}	0.987	0.977	0.969
	X^2	1.495	7.567	3.260
	AIC	23.472	27.697	30.137
	AIC_C	26.472	30.697	33.137
	w_i	0.977*	0.956*	0.708*
	K_F	16.018	18.254	17.164
	n	2.618	2.619	2.572
Freundlich	DPR	46.862	71.000	53.911
	R^2	0.968	0.954	0.967
	R^2_{aj}	0.962	0.945	0.960
	X^2	9.405	9.172	9.890
	AIC	30.930	33.836	31.911
	AIC_C	33.930	36.836	34.911
	w_i	0.023	0.044	0.292

criterion (26.472) and the highest values of Akaike weight (0.977) and R^2 (0.989), making it the model with the highest probability of accurately representing the data. Thus, the Langmuir isotherm assumes that the adsorption process occurs in a monolayer and that the active sites are uniformly distributed (Thongprasong; Thananant, 2022).

In addition to understanding the adsorption mechanisms, the adjustment also allowed for the determination of the maximum adsorption capacity at 99.080 mg g⁻¹ for the temperature of 28 °C. Figure 7 illustrates the fit of the Langmuir isotherm model (28 °C) to the experimental data.

In the literature, research has utilized lignocellulosic materials for the adsorption of the AM dye. In a recent study, Sukmana et al. (2023) investigated the efficiency of rice husk waste for the removal of the MB dye in aqueous solution. By fitting the mathematical model of the Langmuir isotherm, they were able to determine the maximum adsorption capacity to be 9.8 mg g⁻¹. The authors noted that the bioadsorbent showed promising results in the decontamination of the dye. Therefore, the results obtained in this research are superior to those presented by these authors.

Conclusion

The production, preparation, and application of the bioadsorbent using the bark of the species *Mimosa caesalpinifolia* for the adsorption of MB yielded promising results, especially since it utilizes a plant material abundant in the caatinga biome and does not involve chemical modifications that increase costs in large-scale adsorption processes. This study addresses two pressing environmental issues: the

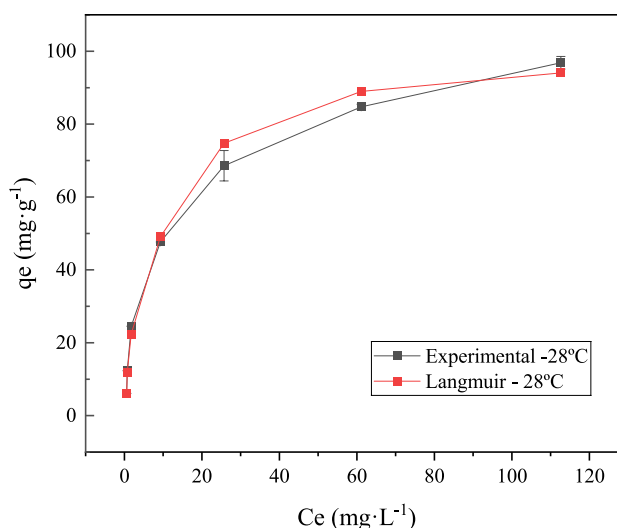


Fig. 7 Comparison between the experimental data and the Langmuir isotherm at a temperature of 28 °C with concentrations ranging from 25 to 500 mg.L⁻¹



accumulation of improperly disposed solid wood waste and the decontamination of wastewater from textile industries.

The morphological analysis allowed for the identification of pore distribution and the functional groups present on the surface of the bioadsorbent. The adsorption tests facilitated the determination of the optimal pH for the adsorption process, as well as the equilibrium time of 60 min and the maximum adsorption capacity of 99.080 mg g⁻¹ at a temperature of 28 °C.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13762-025-07027-7>.

Acknowledgements To the Federal Rural University of the Semi-Arid Region (UFERSA), the Graduate Program in Materials Science and Engineering (PPGCEM), the National University of Engineering (UNI), and the Coordination for the Improvement of Higher Education Personnel (CAPES).

Postgraduate Program in Materials Science and Engineering at the Federal Rural University of Semi-Arid Region and Coordination for the Improvement of Higher Education Personnel (CAPES), Technological Development Center—CDTec, Postgraduate Program in Materials Science and Engineering, PPGCEM/UFPEL, and CNPq (405916/2023-0).

Author Contributions J. B. Souza and L. M. M. Ferreira: Conducting the experiments, analyzing the data, creating the graphs and writing. L. D. Bessa, R. A. S. Vieira and R. C. L. Cisneros: Analyzing the data and creating the graphs. R. R. Melo and S. Khan: Methodology, analyzing the data, creating the graphs, writing, supervision, review and editing.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

Data Availability All relevant data are provided within the main text or the Supplementary Information.

Declarations

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

Ethical Approval This study did not involve human or animal participants.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Akaike, H. (1979) *A Bayesian Extension of the Minimum AIC Procedure of Autoregressive Model Fitting*. *Biometrika*. Available at: <https://www.jstor.org/stable/2335654>.
- Akköz Y, Coşkun R (2023) Cellulose-supported bioadsorbent from natural hemp fiber for removal of anionic dyes from aqueous solution. *Int J Biol Macromol*. <https://doi.org/10.1016/j.ijbiomac.2023.126447>
- Aksakal O, Uzun H (2010) Equilibrium, kinetic and thermodynamic studies of the biosorption of textile dye (Reactive Red 195) onto *Pinus sylvestris* L. *J Hazard Mater* 181(1–3):666–672. <https://doi.org/10.1016/j.jhazmat.2010.05.064>
- Alhashem Z, Farha AH, Mansour SA, Tony MA (2023) Extractability of rice husk waste using green gamma radiation for dye elimination in laboratory-scale sorption system: equilibrium isotherm and kinetic analysis. *Materials* 16(9):3328. <https://doi.org/10.3390/ma16093328>
- Aslan BG, Aslan C, İlhan S (2023) Hydrometallurgical Recovery of Valuable Metals from Hazardous Petrochemical Industry Waste and Kinetic Investigation. *Journal of Sustainable Metallurgy* 9(4):1535–1549. <https://doi.org/10.1007/s40831-023-00745-7>
- Behera AK, Shadangi KP, Sarangi PK (2024) Efficient removal of Rhodamine B dye using biochar as an adsorbent: study the performance, kinetics, thermodynamics, adsorption isotherms and its reusability. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2024.141702>
- Benkhaya S, M'Rabet S, El Harfi A (2020) A review on classifications, recent synthesis and applications of textile dyes. *Inorg Chem Commun* 115:107891
- Bhattacharya R (2023) A review on production and application of activated carbon from discarded plastics in the context of waste treats waste. *J Environ Manage* 325:116613. <https://doi.org/10.1016/j.jenvman.2022.116613>
- Chenna M, Kebaili M, Lardjane N, Drouiche N, Lounici H (2022) Modeling and optimization by RSM for the removal of the dye blue R by coagulation-flocculation process. *Int J Environ Res*. <https://doi.org/10.1007/s41742-022-00413-w>
- Er E, Gazigil L, Yonar T (2024) Electro-oxidation of Indigo Blue aqueous solution for COD and color removal: RSM optimization and pilot-scale study. *Arab J Sci Eng* 49(1):415–428. <https://doi.org/10.1007/s13369-023-08200-1>
- Faria, L.N. (2021) 'Reaproveitamento de resíduos sólidos de madeira na produção de painéis aplicados na construção civil (Reuse of solid wood waste in the production of panels applied in civil construction)', in Tullio, F.B.M. (ed.) *Força, crescimento e qualidade da engenharia civil no Brasil*. Força, Crescimento e Qualidade da Engenharia Civil no Brasil, vol. 3, pp. 102–111. Available at: <https://doi.org/10.22533/at.ed.0000000000>
- Giraldo S et al (2022) Application of orange peel waste as adsorbent for methylene blue and Cd²⁺ simultaneous remediation. *Molecules*. <https://doi.org/10.3390/molecules27165105>
- Guerrero-Pérez MO, Patience GS (2020) Experimental methods in chemical engineering: Fourier transform infrared spectroscopy—FTIR. *Can J Chem Eng*. <https://doi.org/10.1002/cjce.23664>
- Hubbe MA, Azizian S, Douven S (2019) Implications of apparent pseudo-second-order adsorption kinetics onto cellulosic materials: a review. *Bioresour* 14(1):758–806
- İhaddaden S, Aberkane D, Boukerroui A, Robert D (2022) Removal of methylene blue (basic dye) by coagulation-flocculation with biomaterials (bentonite and *Opuntia ficus indica*). *J Water Process Eng*. <https://doi.org/10.1016/j.jwpe.2022.102952>



- Khan I et al (2022) Review on methylene blue: its properties, uses, toxicity and photodegradation. *Water*. <https://doi.org/10.3390/w14020242>
- Lehr M, Miltner M, Friedl A (2021) Removal of wood extractives as pulp (pre-)treatment: a technological review. *SN Appl Sci*. <https://doi.org/10.1007/s42452-021-04873-1>
- Lin F et al (2021) Inner defects elimination and significant reinforcement of rice straw/high-density polyethylene composites by extractives removal process. *J Appl Polym Sci*. <https://doi.org/10.1002/app.50137>
- López-Miranda JL, Silva R, Molina GA, Esparza R, Hernández-Martínez AR, Hernández-Cardeno J, Estévez M (2020) Evaluation of a dynamic bioremediation system for the removal of metal ions and toxic dyes using *Sargassum* spp. *J Mar Sci Eng* 8(11):899. <https://doi.org/10.3390/jmse8110899>
- Ma X et al (2022) A novel natural lignocellulosic biosorbent of sunflower stem-pith for textile cationic dyes adsorption. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2021.129878>
- Mandale P et al (2024) Adsorption of malachite green dye from aqueous solution on bioadsorbent as low-cost adsorbent, *Materials Today: Proceedings* [Preprint] <https://doi.org/10.1016/j.matpr.2024.01.048>
- Manshoven S, Christis M, Vercalsteren A, Arnold M, Nicolau M, Lafond E (2019) Textiles and the environment in a circular economy. *Eionet Report - ETC/WMGE* 6:1–56
- Mashkoo F, Nasar A (2020) Magsorbents: Potential candidates in wastewater treatment technology – A review on the removal of methylene blue dye. *J Magn Magn Mater*. <https://doi.org/10.1016/j.jmmm.2020.166408>
- Mbarki F et al (2022) Low-cost activated carbon preparation from Corn stigmata fibers chemically activated using H₃PO₄, ZnCl₂ and KOH: study of methylene blue adsorption, stochastic isotherm and fractal kinetic. *Ind Crops Prod*. <https://doi.org/10.1016/j.indcrop.2022.114546>
- Mirhosseini H, Shamspur T, Mostafavi A (2022) Novel adsorbent g-C₃N₄/ZnV₂O₄ for efficient removal of crystal violet dye: removal process optimization, adsorption isotherms, and kinetic modeling. *Appl Organomet Chem* 36(12):e6867. <https://doi.org/10.1002/aoc.6867>
- Moorthy AK, Rathi BG, Shukla SPS, Kumar K, Bharti VS (2021) Acute toxicity of textile dye methylene blue on growth and metabolism of selected freshwater microalgae. *Environ Toxicol Pharmacol* 82:103552. <https://doi.org/10.1016/j.etap.2020.103552>
- Nayak AK, Pal A (2021) Enhanced adsorption of gentian violet dye from water using lignocellulosic agricultural waste modified with di- and tri-carboxylic acids: artificial intelligence modeling, practical comprehension, mechanistic and regeneration analyses. *J Environ Chem Eng*. <https://doi.org/10.1016/j.jece.2021.105578>
- Nindjio GFK et al (2022) Lignocellulosic-based materials from bean and pistachio pod wastes for dye-contaminated water treatment: optimization and modeling of indigo carmine sorption. *Polymers*. <https://doi.org/10.3390/polym14183776>
- Phawachalotorn, C. and Suwanpayak, N. (2021) ‘The efficiency of mangosteen peel for dye removal’, in *Journal of Physics: Conference Series*. IOP Publishing Ltd. Available at: <https://doi.org/10.1088/1742-6596/1719/1/012061>.
- Prabhakar Y, Gupta A, Kaushik A (2022) Using indigenous bacterial isolate *Nesterenkonia lacusekhoensis* for removal of azo dyes: a low-cost ecofriendly approach for bioremediation of textile wastewaters. *Environ Dev Sustain* 24(4):5344–5367. <https://doi.org/10.1007/s10668-021-01661-0>
- Quaff AR, Venkatesh S, Venkatesh K (2021) Degradation of azo dye by ozone oxidation: cost analysis and buffering effects on dye decomposition. *Natl Acad Sci Lett* 44(4):339–341. <https://doi.org/10.1007/s40009-020-01008-9>
- Rêgo Júnior AG, Araújo IPR, Souza JB, Melo TNTF, Vieira RAS, Souza YCS, Xavier MS, Queiroz LR, Alves JIS, Menezes FLG, Júnior FFM, Khan S (2023) Potential applications of low-cost Brazilian corn starch as an adsorbent for removing the Acid Violet 19 contaminant from river water. *Z Phys Chem*. <https://doi.org/10.1515/zpch-2023-0346>
- Sahu S et al (2020) Kendu (*Diospyros melanoxylon* Roxb) fruit peel activated carbon—an efficient bioadsorbent for methylene blue dye: equilibrium, kinetic, and thermodynamic study. *Environ Sci Pollut Res* 27(18):22579–22592. <https://doi.org/10.1007/s11356-020-08561-2>
- Sawalha H, Bader A, Sarsour J, Al-Jabari M, Rene ER (2022) Removal of dye (methylene blue) from wastewater using biochar derived from agricultural residues in Palestine: performance and isotherm analysis. *Processes* 10(10):2039. <https://doi.org/10.3390/pr10102039>
- Sharma C, Chopra L (2022) Degrading azo dye by wet air oxidation: application of response surface methodology. *Mater Today Proc* 52:345–350. <https://doi.org/10.1016/j.matpr.2021.10.090>
- Simonin JP (2016) On the comparison of pseudo-first order and pseudo-second order rate laws in the modeling of adsorption kinetics. *Chem Eng J* 300:254–263. <https://doi.org/10.1016/j.cej.2016.04.079>
- Solovyeva MV, Shkatulov AI, Gordeeva LG, Fedorova EA, Krieger TA, Aristov YI (2021) Water vapor adsorption on CAU-10-X: effect of functional groups on adsorption equilibrium and mechanisms. *Langmuir* 37(2):693–702. <https://doi.org/10.1021/acs.langmuir.0c02729>
- Souza AP, Costa FCP, Alencar RF, Barbosa Lima SF (2018) Exploração e utilização do potencial madeireiro da Caatinga no município de Aurora – estado do Ceará (Exploration and utilization of the timber potential of the Caatinga in the municipality of Aurora – state of Ceará). *Pesquisa e Ensino Em Ciências Exatas e Da Natureza* 2(2):158. <https://doi.org/10.29215/pecen.v2i2.1070>
- Subekti R, Helmiyati H (2020) Sodium alginate-TiO₂-bentonite nanocomposite synthesis for photocatalysis of methylene blue dye removal. *IOP Conf Series Mater Sci Eng* 763(1):012018. <https://doi.org/10.1088/1757-899X/763/1/012018>
- Sukmana H et al (2023) Hungarian and Indonesian rice husk as bio-adsorbents for binary biosorption of cationic dyes from aqueous solutions: a factorial design analysis. *Heliyon*. <https://doi.org/10.1016/j.heliyon.2023.e17154>
- Suman H, Yadav DK, Sangal VK, Vashishtha M (2023) Parametric study for the treatment of tannery dye wastewater by electro-oxidation. *J Indian Chem Soc* 100(4):100961
- Teshager FM, Habtu NG, Mequanint K (2024) Coupled adsorption–phytoremediation treatment of cellulose-reactive blue dye in a sustainable multi-step pilot-scale process. *Environ Sci Pollut Res* 31(6):8736–8750. <https://doi.org/10.1007/s11356-023-31547-9>
- Thongprasong O, Thananant H (2022) Adsorption of iodine and reactive dye molecules from water using chemically modified and unmodified lignocellulosic powders (*Ficus Lyrata* seeds). *Res Chem Intermed* 48(11):4837–4856. <https://doi.org/10.1007/s11164-022-04824-4>
- Top Y, Adanur H, Öz M (2018) Type, quantity, and re-use of residues in the forest products industry in Trabzon, Turkey. *BioResources* 13(1):1745–1760. <https://doi.org/10.15376/biores.13.1.1745-1760>
- Venceslau ADFA et al (2021) Removal of methylene blue from an aqueous medium using atemoya peel as a low-cost adsorbent. *Water Air Soil Pollut*. <https://doi.org/10.1007/s11270-021-05414-7>



- Vojnović B et al (2022) Influence of initial pH value on the adsorption of reactive black 5 dye on powdered activated carbon: kinetics, mechanisms, and thermodynamics. *Molecules*. <https://doi.org/10.3390/molecules27041349>
- Wang R-F, Deng L-G, Li K, Fan X-J, Li W, Lu H-Q (2020) Fabrication and characterization of sugarcane bagasse–calcium carbonate composite for the efficient removal of crystal violet dye from wastewater. *Ceram Int* 46(17):27484–27492. <https://doi.org/10.1016/j.ceramint.2020.07.237>
- Weber WJ, Morris JC (1963) Kinetics of adsorption on carbon from solution. *J San Eng Div ASCE* 89(2):31–60
- Worch E (2021) Adsorption Technology in Water Treatment: Fundamentals, Processes, and Modeling, 2nd edn. De Gruyter GmbH, Berlin. <https://doi.org/10.1515/9783110715507>
- Yadav S et al (2022) Pennisetum glaucum lignocellulosic adsorbent modified with CNT for the removal of cationic dyes from individual and multi-component systems. *Cellulose* 29(14):7803–7821. <https://doi.org/10.1007/s10570-022-04756-7>
- Yang X et al (2022) Characteristics and aqueous dye removal ability of novel biosorbents derived from acidic and alkaline one-step ball milling of hickory wood. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2022.136610>
- Zawadzki P, Deska M (2021) Degradation efficiency and kinetics analysis of an advanced oxidation process utilizing ozone, hydrogen peroxide and persulfate to degrade the dye rhodamine B. *Catalysts* 11(8):974. <https://doi.org/10.3390/catal11080974>
- Zhang J et al (2022) 3D porous structure-inspired lignocellulosic biosorbent of Medulla tetrapanacis for efficient adsorption of cationic dyes. *Molecules*. <https://doi.org/10.3390/molecules27196228>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

J. B. de Souza¹ · L. M. M. Ferreira¹ · L. D. Bessa¹ · R. A. da Silva Vieira¹ · R. López² · S. Khan^{1,3}  · R. R. de Melo¹

✉ S. Khan
sabir.khan@ufpel.edu.br

¹ Federal Rural University of the Semi-Arid, Engineering Center, Avenida Francisco Mota, 572, Bairro Costa E Silva, Mossoró, Rio Grande Do Norte 59625-900, Brazil

² National University of Engineering, Av. Túpac Amaru 210, Rímac 15333, Peru

³ Graduate Program in Materials Science and Engineering (PPGCEM), Technological Development Center, Federal University of Pelotas (UFPEL), Pelotas, RS 96010-610, Brazil

