Evaluation of Ocotea puberula bark powder (OPBP) as an effective adsorbent to uptake crystal violet from colored effluents: alternative kinetic approaches

Jordana Georgin1,2 · Dison S. P. Franco1 · Matias Schadeck Netto1 · Daniel Allasia2 · Marcos L. S. Oliveira3,4 · Guilherme L. Dotto1

Received: 5 February 2020 / Accepted: 13 April 2020 / Published online: 30 April 2020
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

Abstract
The Ocotea puberula bark powder (OPBP) was evaluated as an effective adsorbent for the removal of crystal violet (CV) from colored effluents. OPBP was characterized and presented a surface with large cavities, organized as a honeycomb. The main functional groups of OPBP were O-H, N-H, C=O, and C-O-C. The adsorption of CV on OPBP was favorable at pH 9 with a dosage of 0.75 g L\(^{-1}\). The Avrami model was the most suitable to represent the adsorption kinetic profile, being the estimated equilibrium concentration value of 3.37 mg L\(^{-1}\) for an initial concentration of 50 mg L\(^{-1}\) (CV removal of 93.3%). The equilibrium was reached within 90 min. The data were better described by the Langmuir isotherm, reaching a maximum adsorption capacity of 444.34 mg g\(^{-1}\) at 328 K. The Gibbs free energy ranged from \(-26.3554\) to \(-27.8055\) kJ mol\(^{-1}\), and the enthalpy variation was \(-11.1519\) kJ mol\(^{-1}\). The external mass transfer was the rate-limiting step, with Biot numbers ranging from 0.0011 to 0.25. Lastly, OPBP application for the treatment of two different simulated effluents was effective, achieving a removal percentage of 90%.

Keywords Adsorption · Biot number · Crystal violet · Mass transfer parameters · Ocotea puberula

Introduction
The increase in the world population led to an increase in the consumption of industrial products and, consequently, the industrial activities were intensified. In this scenario, industries that use dyes also increased their production, thus generating more colored effluents (Anbia and Salehi 2012). Color in industrial effluents can be observed even at lower dyes concentration (< 1 mg L\(^{-1}\)), being highly visible and undesired (Essawy et al. 2008). The international legislation is stringent with regard to the content of organic material present in these effluents, since many dyes are toxic and carcinogenic, being a serious risk to living aquatic organisms. Furthermore, dyes can also affect the photosynthetic activity of aquatic plants (Honorato et al. 2015). Crystal violet (CV) is a triphenylmethane dye, being carcinogenic and mutagenic, but it is still used on a large industrial scale for tissue dyeing and laboratory scale for biological staining of various living tissues and organs (Sarma et al. 2016). CV can cause skin irritation, nausea, and vomits in humans. At higher concentrations, it may cause respiratory complications, kidney failure, and permanent blindness. In this context, it is necessary for the application of treatment techniques before the release of these effluents into the environment (Quresshi et al. 2015).

Adsorption has been gaining space in the scientific community as an excellent operation to treat effluents. It is an efficient method, with low cost and ease operation.
Adsorption is extremely competitive and favorable when used coupled with low-cost adsorbents such as vegetal biomasses (Uddin et al. 2017). In this sense, various adsorbents have been developed and tested; for example, Tahir et al. (2016) used the Eucalyptus angophoroides bark for the removal of solar red and brittle blue direct dyes; Silva and collaborators (Silva et al. 2018) have reported that the Acacia mearnsii can be used for the removal of crystal violet; Afroze et al. (2016) prepared an adsorbent from Eucalyptus sheathiana for the zinc removal from waters; the coniferous pine bark (P. roxburghii) was tested for the removal of crystal violet (Ahmad 2009); Sartape et al. (2017) used the Limonia acidissima bark for the removal of malachite green from effluents; Jia et al. (2017) utilized Cortaderia selloana flower spikes in the removal of methylene blue dye. Weber et al. have prepared an adsorbent from Carica papaya L. for the removal of direct black 38, yellow tartrazine, and amaranth (Weber et al. 2013, 2014). The aforementioned studies have shown the importance of searching for environmentally relevant material. Furthermore, this adsorbent should be available in larger quantities and present low cost, such as material derived from biomasses.

The Ocotea puberula is an evergreen tree species belonging to the Lauraceae family, which can be normally found in Brazil, Paraguay, and Argentina (Zangaro et al. 2003). It has a large size, reaching 30 m height. Its wood is most exploited in the subtropical climate because it is a light wood of large size, reaching 30 m height. Its wood is most exploited in Brazil, Paraguay, and Argentina (Zangaro et al. 2003). It has a large size, reaching 30 m height. Its wood is most exploited in Brazil, Paraguay, and Argentina (Zangaro et al. 2003).

Preparation of Ocotea puberula bark powder adsorbent

The Ocotea puberula bark was obtained in the region of the Federal University of Santa Maria, Brazil. Firstly, the bark chips attached to the tree trunk were removed and washed with distilled water to remove all dust and other impurities. Secondly, the bark was taken to an oven and dried at 50 °C for 48 h to remove the moisture excess. The material was ground using a knife mill and further sieved (passing in mesh 80 and retained in mesh 100). Third, the bark powder from Ocotea puberula was washed using an ethanol solution (60% v/v) at room temperature for 1 h under the agitation of 150 rpm. This process was executed until the solution was transparent, thus removing the extractives present in the bark. Lastly, the material was separated through decantation and dried once again at 50 °C for 48 h. As a result, it was obtained an adsorbent powder which was identified as Ocotea puberula bark powder (OPBP). The physical characteristics of the OPBP are as follows: average particle diameter (dₚ) of 160 μm; void fraction (ε) of 0.3264; tortuosity factor (τ) of 8.58; solid density (ρₛ) 181.3 kg m⁻³; particle density (ρₚ) 122.1 kg m⁻³; external surface area of OPBP (S) 2068.9 cm² g⁻¹; moisture content 4.5% wet basis.

Characterization of Ocotea puberula bark powder adsorbent

The determination of chemical groups of the OPBP was done using Fourier-transform infrared spectroscopy (FT-IR) (Shimadzu, model IR-Prestige 21, Japan). For this, 40 mg of material was pressed with dry potassium bromide. The spectrum was obtained with a 4-cm⁻¹ resolution with a sequential scan in the range of 4500-500 cm⁻¹. The surface analysis for the OPBP was made through scanning electron microscopy (SEM) model Vega 3 SB from Tescan (Czech Republic) with a working voltage of 10 kV and magnifications of 500, 1000, 2000, and 3000 times. Last, the crystallographic phase was determined through X-ray powder diffractometry using a Miniﬁx 300 from Rigaku (Brazil). Lastly, the point of zero charge (pHₚzc) was determined through the pH test. It was prepared a solution of 50 mL of NaCl (1 mol L⁻¹) and added 0.7 g of adsorbent. The initial pH and final pH (after 48 h of agitation at 25 °C) were measured (Khormaei et al. 2007).
CV adsorption on OPBP: batch tests

The effects of various parameters on the adsorption of CV onto OPBP were evaluated through the following experiments:

- The OPBP dosage effect was analyzed using 0.50, 0.75, 1.00, 1.25, and 1.50 g L\(^{-1}\) of the adsorbent. The material was added to 50 mL of CV solution with a dye concentration of 50 mg L\(^{-1}\). The solution was then agitated for 180 min at room temperature.
- The pH effect was evaluated from 5.0 to 9.0. It was used 0.75 g L\(^{-1}\) of OPBP with 50 mL of CV solution with an initial concentration of 50 mg L\(^{-1}\). It was agitated for 180 min at room temperature. The initial pH values were adjusted using NaOH and HCl according to each experiment;
- The kinetic curves were obtained using the best conditions obtained from the pH and dosage tests (0.75 g L\(^{-1}\) and pH 9) for different initial concentrations of CV (50, 100, 150, and 250 mg L\(^{-1}\)). For each test, it was used 50 mL of CV at room temperature, and samples were collected at 0, 2, 5, 10, 15, 20, 30, 45, 60, 120, and 180 min.
- The equilibrium data were obtained for the temperatures (298, 308, 318, and 328 K) for each experiment. The solutions were agitation: 2S + A \(\rightarrow\) AS (Ho and Mckay 1998). The fractional Avrami model (Eq. (7)), traditionally used for describing the particle nucleation, can also be applied for describing the adsorption kinetics (Avrami 1939). The Elovich model (Eq. (8)) assumes chemical adsorption on a heterogeneous surface, with a rate dependent on the surface coverage (Elovich and Larinov 1962); the second-order kinetic/equilibrium model (Eq. (9)) proposed by Weber-Miller, is a solution for the Langmuir kinetics (Weber and Miller 1988); and the Loebenstein model (Eq. (10)), which is a derivation of the Langmuir kinetics, considering only the adsorption effect for batch adsorption (Loebenstein 1962).

\[
C_i = C_0 \exp(-k_1 t) + C_{e1}(1 - \exp(-k_1 t)) \tag{4}
\]

\[
C_i = C_{e2} + \frac{1}{D_0 t + \frac{1}{(C_0 - C_{e2})}} \tag{5}
\]

\[
C_i = C_{en} + \left( \frac{1}{(n + 1)k_n D_0^n t + \left(\frac{C_0}{C_{e, n}}\right)^n} \right)^{1/n} \tag{6}
\]

\[
C_i = C_0 \exp(-k_A t^n) + C_{eA}(1 - \exp(-k_A t^n)) \tag{7}
\]

\[
C_i = C_0 - \frac{D_0}{\beta} \ln(1 + \beta \alpha t) \tag{8}
\]

\[
C_i = C_0 - \frac{1}{2} \left\{ \varphi - \frac{\eta}{\tanh\left(\frac{\eta k_L^\alpha t}{2}\right)} + \tanh^{-1}\left(\frac{\eta}{\varphi}\right) \right\} \tag{9}
\]

\[
\varphi = C_0 + D_0 q_L + \frac{1}{k_L^\gamma}, \quad \gamma = \sqrt{\varphi^2 - 4D_0 q_L C_0} \tag{9.a}
\]

\[
C_i = C_0 - q_{Loe} D_0 \left[ \frac{1 - \exp(-\omega C_0 k_{Loe} t)}{C_0} - \exp(-\omega C_0 k_{Loe} t) \right] \tag{10}
\]

\[
\omega = \frac{q_{Loe} D_0}{C_0} - 1 \tag{10.a}
\]

\[ R = \frac{(C_0 - C_i)}{C_0} \times 100\% \tag{1}
\]

\[ q_i = \frac{(C_0 - C_i)}{D_0} \tag{2}
\]

\[ q_e = \frac{(C_0 - C_e)}{D_0} \tag{3}
\]

Alternative kinetic modeling

In the studies of liquid-phase adsorption, the kinetic curves are normally presented as \(q_i\) versus \(t\). Alternatively, all models used in this work were mathematically modified as \(C_i\) versus \(t\). The mathematical procedure used to modify the kinetic equations is presented in the supplementary material. The models used were pseudo-first-order model (Eq. (4)), proposed by Lagergren (1898), which takes the assumption that the adsorption occurs as a non-reversible reaction, such as S + A \(\rightarrow\) AS; pseudo-second-order model (Eq. (5)) is an empirical variation of the first order, which considers the following reaction: 2S + A \(\rightarrow\) AS\(_2\) (Ho and Mckay 1998). The general-order model (Eq. (6)) consists that the reaction can be of n order (Liu and Shen 2008). The fractional Avrami model (Eq. (7)), is a solution for the Langmuir kinetics (Weber and Miller 1988); and the Loebenstein model (Eq. (10)), which is a derivation of the Langmuir kinetics, considering only the adsorption effect for batch adsorption (Loebenstein 1962).

Isotherms and thermodynamics

For describing the isotherms, the models of Langmuir (Langmuir 1918) (Eq. (11)), Freundlich (1906) (Eq. (12)), and Sips (Sips 1948) (Eq. (13)) were used.
\[ q_e = q_L \frac{K_L C_e}{1 + K_L C_e} \]  \hspace{1cm} (11)

\[ q_e = K_F C_e^{1/n} \]  \hspace{1cm} (12)

\[ q_e = q_{mb} \frac{K_S C_m^n}{1 + K_S C_m^n} \]  \hspace{1cm} (13)

For the thermodynamic estimations, it was used the equilibrium constant, which was estimated from the best isotherm model, following the methodology proposed by Lima et al. (2019), here presented by Eqs. (14)-(17).

\[ K_e = \frac{K M W \gamma^{CV}}{\gamma} \]  \hspace{1cm} (14)

\[ \Delta G^0 = -RT \ln(K_e) \]  \hspace{1cm} (15)

\[ \Delta G^0 = \Delta H^0 - T \Delta S^0 \]  \hspace{1cm} (16)

\[ \ln(K_e) = \frac{\Delta S^0}{R} - \frac{\Delta H^0}{RT} \]  \hspace{1cm} (17)

**Mass transfer evaluation**

Overall, the adsorption mechanism can be divided into two different steps: the external and the internal mass transfer. The external mass transfer depends on the external mass transfer coefficient \( (k_f) \). In the case of the internal mass transfer, it can be due to the surface \( (D_s) \) or effective pore diffusion \( (D_p) \). In general, the determination of these parameters, in special the \( D_s \) is often dependent on numerical solutions of phenomenological models. In this context, Chu (2019) and Yuan et al. (2020) proposed a simplified correlation. Here, we have used a modification of this methodology, presented by Eqs. (18)-(20):

\[
\begin{bmatrix}
\text{Total mass transfer} \\
\text{resistance}
\end{bmatrix} = \sum \begin{bmatrix}
\text{Individual mass transfer} \\
\text{resistances}
\end{bmatrix}
\]

\[
1 = \frac{(r_L + 1)}{2} \left( \frac{1}{N_L} + \frac{1}{N_{int}} \right)
\]

\[
1 = \frac{1}{N_p} + \frac{1}{N_S}
\]

\[
N_S = k_l \rho_p q_L
\]

\[
N_F = \frac{3k_f}{R}
\]

\[
N_S = \frac{15D_p \rho_p q_0}{R^2 C_0}
\]

\[
N_p = \frac{15D_p}{R^2}
\]

In this case, the objective is the determination of \( D_S \); however, for this, the other mass transfer parameters need to be estimated. The first one is the lumped kinetics \( (k_i) \); this parameter is obtained from the regression of a model that uses the Langmuir kinetics, such as the Weber-Miller or Loebenstein. Second is the film coefficient, which can be estimated through the methodology proposed by Furusawa and Smith (1973) (Eq. (25)).

\[ k_f = -\frac{dC_i/C_0}{dt} \bigg|_{t=0} \]  \hspace{1cm} (25)

The third step is the determination of the effective pore diffusion coefficient, which can be estimated from the molecular diffusivity \( (D_{AB}) \) for the CV dye, using the Wilke and Chang (1955) correlation, and the relation of the molecular diffusivity and the pore diffusion (Eqs. (26)-(28)).

\[ D_{AB} = 7.4 \times 10^{-8} \left[ \frac{\left( \frac{M_B}{V_A} \right)^{0.5}}{\eta_B V_A^{0.5}} \right] \]  \hspace{1cm} (26)

\[ D_p = \frac{D_{AB} \epsilon}{\tau} \]  \hspace{1cm} (27)

\[ \tau = \frac{(2 - \epsilon)^2}{\epsilon} \]  \hspace{1cm} (28)

where \( x = 2.6, M_B = 18.02 \text{ g mol}^{-1}, \eta_B = 0.904 \text{ cp}, T = 298.15 \text{ K}, \text{ and } V_A = 352.31 \text{ cm}^3 \text{ mol}^{-1} \). The values of \( D_{AB} \) and \( D_p \) were \( 4.74 \times 10^{-7} \text{ and } 1.80 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1} \), respectively.

**Fit evaluation**

The determination of fit quality for each applied model was made using: coefficient of determination \( (R^2) \) (Eq. (29)), adjusted determination coefficient \( (R^2_{adj}) \) (Eq. (30)), average relative error (ARE) (Eq. (31)), and mean squared error (MSE) (Eq. (32)). All the parameters estimations were made using a script programming on Matlab 2017.

\[ R^2 = 1 - \frac{\sum_{i=1}^{n} \left( y_{exp} - y_{pred}^i \right)^2}{\sum_{i=1}^{n} \left( y_{exp} - \bar{y}_{exp} \right)^2} \]  \hspace{1cm} (29)

\[ R^2_{adj} = 1 - (1 - R^2) \frac{(n - 1)}{(n - p - 1)} \]  \hspace{1cm} (30)

\[ \text{ARE} = \frac{100\%}{n} \sum_{i=1}^{n} \left| \frac{y_{exp} - y_{pred}}{y_{exp}} \right| \]  \hspace{1cm} (31)

\[ \text{MSE} = \frac{1}{n - p} \sum_{i=1}^{n} \left( y_{exp} - y_{pred}^i \right)^2 \]  \hspace{1cm} (32)
Treatment of simulated effluents

OPBP was tested to treat simulated effluents, aiming to verify its potential in real industrial applications. In this case, two different effluents were prepared (A and B), both composed by different mixtures of dyes and salts (Table 1) (Schadeck Netto et al. 2019). For these experiments, 4.5 g L$^{-1}$ of OPBP was put in contact with the effluents, and the mixtures were stirred at 150 rpm for 2 h (room temperature). The treatment efficiency was determined by the ratio between the areas below the spectroscopic curves before and after the adsorption for each effluent solution (Georgin et al. 2018).

Results and discussion

Characteristics of Ocotea puberula bark powder

The structure of OPBP was analyzed through the XRD pattern, as shown in Fig. 1a. It is possible to observe that the material presented a large band from 10 to 30° and is correspondent to the crystalline phase of the cellulose (Wang et al. 2016). Also, the XRD pattern indicates that the material is mainly formed by an amorphous configuration (Xu et al. 2007).

The FT-IR technique was used for the identification of the functional groups that constitute the OPBP and, possibly, is responsible for the CV adsorption. The spectrum is presented in Fig. 1b. The broad and intense band on the region of 3434 cm$^{-1}$ is related to the OH elongation. The band at 2929 cm$^{-1}$ can be attributed to the OH bonds related to the methyl group (-COH). The band observed at 1740 cm$^{-1}$ can be related to the carbonyl (C=O) of carboxylic acids or esters. The region of 1649 cm$^{-1}$ is characteristic of the aromatic fractions present in the lignin structure. The band at 1462 cm$^{-1}$ can be attributed to the elongation vibration of ether groups. Furthermore, the band around 1371 cm$^{-1}$ is correspondent to the C-H bond of the methyl group. Besides that, the band centered at 1250 cm$^{-1}$ can be associated with the stretching of the ester group vibration. The band at 1119 cm$^{-1}$ is related to the C-O anhydride bonds. Lastly, the band 1050 cm$^{-1}$ is attributed to the C-OH and C-O-C bonds, while the sign of 593 cm$^{-1}$ is due to the presence of the aromatic chains.

The SEM images, with different magnifications, were performed to investigate the surface morphology of OPBP. The images are presented in Fig. 2. It was verified that the adsorbent is constituted of shapeless and asymmetric particles with large cavities (Figs. 2 a and b). The surface of these particles (Fig. 2 c and d) presents large cavities organized like a honeycomb. Such characteristics have been also found in the bark of another tree species (Handroanthus albus) used to remove methylene blue dye (Hernandes et al. 2019).

In summary, the adsorbent proposed in this work (OPBP) contains intrinsic characteristics that are interesting for dyes adsorption purposes, such as, an organized honeycomb structure and a series of functional groups on the surface.

Table 1 Composition of the simulated effluents

| Dyes and compounds                      | Concentration (mg L$^{-1}$) | $\lambda_{\text{max}}$ (nm) |
|----------------------------------------|-----------------------------|-----------------------------|
| Effluent A                             |                             |                             |
| Crystal violet                         | 100                         | 590                         |
| Methylene blue                         | 60                          | 664                         |
| Rhodamine B                            | 50                          | 610                         |
| Malachite green                        | 50                          | 615                         |
| Sodium chloride (NaCl)                 | 100                         |                             |
| Sodium carbonate (Na$_2$CO$_3$)        | 100                         |                             |
| pH measured                            | 9.2                         |                             |
| Effluent B                             |                             |                             |
| Crystal violet                         | 100                         | 590                         |
| Methylene blue                         | 50                          | 664                         |
| Brilliant blue                         | 50                          | 630                         |
| Basic fuchsia                          | 50                          | 546                         |
| Sodium chloride (NaCl)                 | 100                         |                             |
| Sodium carbonate (Na$_2$CO$_3$)        | 100                         |                             |
| pH measured                            | 8.7                         |                             |

Fig. 1 a XRD pattern and b FT-IR spectrum of OPBP adsorbent.
Effects of OPBP dosage and pH on CV adsorption

The effect of OPBP dosage on the CV adsorption is presented in Fig. 3a. The CV removal percentage \((R)\) increased from 84.42 to 95.32% with the rise of OPBP dosage. This increase is due to the presence of more adsorption sites at high OPBP dosages; thus, the dye molecules are quickly allocated. Another important factor is the behavior of the adsorption capacity. When the values of OPBP dosage increased from 0.5 to 1.5 g L\(^{-1}\), the adsorption capacity decreased from 79.69 to 30.0 mg g\(^{-1}\). Liu and collaborators (Liu et al. 2015) obtained a similar removal percentage of acid blue 93 and methylene blue using a porous biosorbent based on cellulose. To determine the best dosage, \(R\) and \(q\) were considered. It was concluded that the use of 0.75 g L\(^{-1}\) furnishes excellent values of removal percentage (higher than 90%) and suitable values of adsorption capacity (around 60 mg g\(^{-1}\)).

The pH and \(pH_{pzc}\) are dominant parameters that govern the adsorption in the liquid phase (Martinez et al. 2006). These parameters offer information about the ionization degree of the adsorbate, solution chemistry, and surface functional groups of the adsorbent (Bairagi et al. 2011). Figure 3b shows the CV adsorption capacity as a function of the initial pH of the solution, while Fig. 3c depicts the point of zero charge (\(pH_{pzc}\)) of the OPBP adsorbent. It was found that the adsorption capacity increased from 39.43 to 45.95 mg g\(^{-1}\) when pH increased from 5 to 9. At first, it can be seen that the \(pH_{pzc}\) of the OPBP is 8.1 (Fig. 3c). So, the surface of OPBP is positively charged at pH values lower than 8.1, neutral at pH 8.1, and negatively charged at pH values higher than 8.1. The CV dye, in turn, is a cation in solution. In conclusion, the pH effect can be explained as follows: at lower pH values (5 to 8), there is a competition between the CV cations and the H\(^+\) ions in solution to attain the adsorption sites, or/and a repulsion of the CV dye molecules caused by the positive surface of the OPBP. Because of this, there is a lower adsorption capacity. At pH values higher than 8.1, the OPBP surface becomes deprotonated, so, is attractive for the positive CV molecules, and leads to a higher adsorption capacity. Based on this effect and the results, pH 9 was chosen for the study of the kinetics and equilibrium curves.
Kinetic profiles and alternative modeling

The adsorption kinetic is an important tool used to evaluate the required time for the system to reach equilibrium. In some cases, provides information in relation to the adsorption mechanisms (Vuono et al. 2017). The concentration decay curves for CV adsorption onto OPBP are depicted in Fig. 4. For all initial CV concentrations, the curves indicated a fast decrease in the CV concentration until the first 20 min. Then, the adsorption rate has decreased, tending to the equilibrium concentration. The equilibrium was reached within 120 min for all initial CV concentrations. In the case of $C_0 = 50$ mg L$^{-1}$, the equilibrium concentration was 5.05 mg L$^{-1}$, representing 90% of dye removal. For the initial concentrations of 100, 150, and 250 mg L$^{-1}$, the equilibrium concentrations were equivalent to 19.64, 53.33, and 113.21 mg L$^{-1}$, respectively. As a consequence, the CV removal percentages were, respectively, 80.3%, 64.4%, and 54.7%.

In this work, pseudo-first-order, pseudo-second-order, general-order, Avrami, Elovich, Weber-Miller, and Loebenstein models were used to find information about the kinetic process. Alternatively, these models were mathematically modified as $C_t$ versus $t$. The kinetic parameters and the respective statistical indicators are depicted in Table 2. From a brief observation, it is possible to conclude that the Avrami model was the most suitable to describe the CV concentration decay curves. This model presented the highest values of $R^2$ and $R^2_{adj}$ (between 0.991 and 0.999), with the lowest ARE ($< 2.8\%$) and MSE ($< 3.53$ (mg L$^{-1}$)$^2$). Furthermore, the Avrami model was able to predict the equilibrium concentration. For example, at $C_0$ of 250 mg L$^{-1}$, the predicted value was 109.37 mg L$^{-1}$ and the experimental was 113.21 mg L$^{-1}$. Evidently, the parameter $C_{Av}$ increased with the initial CV concentration, since more dye molecules are remaining in solution at higher $C_0$ values. The parameter $k_{Av}$, related with the adsorption rate, presented little changes in the initial concentrations from 50 to 150 mg L$^{-1}$, but presented a large increase when the initial concentration increased to 250 mg L$^{-1}$. This shows that at higher CV concentrations in the solution, the adsorption was faster. This is evidence that the process is strongly affected by the external mass transfer, which, in turn, depends on the concentration gradient between the bulk solution and the external surface of the adsorbent.

In parallel, it is also required the selection of a model with a Langmuir kinetics basis, to estimate the mass transfer parameters (lumped kinetics ($k_t$)) (see Eq. (21)). In this case, we have Weber-Miller and Loebenstein (Table 2). From a brief comparison of the statistical parameters in Table 2, it can be concluded that the Loebenstein model can describe the experimental data better compared to the Weber-Miller model. Thus, it was selected for the determination of the mass transfer parameters.

Equilibrium isotherms and thermodynamics

The isotherms are used to relate the adsorption capacities and the solution concentrations at the equilibrium, here presented in Fig. 5. At first, it can be noticed that the isotherm curves were favorable, providing high adsorption capacities coupled to high removal percentages. Subsequently, it is possible to observe that the adsorption capacities were directly favored by the temperature. Considering $C_0 = 500$ mg L$^{-1}$, the equilibrium adsorption capacity ranged from 262.5 to 399.2 mg g$^{-1}$ when the temperature increased from 298 to 328 K. This behavior is associated with the thermal collision effect, due to the increase of temperature. This causes an increase in the system energy, facilitating the interaction of the dye with the adsorbent surface. Also, a modification in the adsorbent surface can occur, such as swelling, leading to an improvement in adsorption at higher temperatures (Bonilla-Petriciolet et al. 2017). A similar trend was reported by Liu et al. (2018) in the adsorption of methylene blue onto a nutshell, obtaining a variation of 53.6 to 80.4 mg g$^{-1}$ with the temperature increase from 298 to 318 K, for the concentration variation of 50 to 200 mg L$^{-1}$. Georgin et al. (2019) used the Cedrella fissilis bark for the adsorption of RED 97, obtaining a similar behavior, where the adsorption capacity ranged from 392.68 to 422.87 mg g$^{-1}$ for the temperature range of 298 to 328 K with a concentration variation from 50 to 450 mg L$^{-1}$.

The estimated parameters for the Langmuir, Freundlich, and Sips models are presented in Table 3. Analyzing the obtained values, it was observed that the Langmuir model is the most suitable for describing the adsorption of CV, concerning the Freundlich and Sips model. For the Langmuir model, the higher values for $R^2$ and $R^2_{adj}$ and lower values for ARE and MSE were found. Furthermore, the Langmuir parameter ($q_L$) presented a directly proportional relationship with the temperature, indicating an endothermic process.
One important aspect of the development and selection of alternative adsorbents is how the material performs concerning other reports in the literature, in terms of maximum adsorption capacity. Thus, a comparison between OPBP and the reported materials was made, here presented in Table 4. A direct observation indicates that the OPBP is the second-best material in relation to the adsorption capacity, staying behind the graphene oxide nanocomposite, reported by Puri and Sumana (2018). Thus, OPBP can be a viable alternative to uptake CV from aqueous media.

Based on the values of the Langmuir constant ($K_L$), it was estimated the equilibrium constant ($K_e$) for the determination of the thermodynamic parameters ($\Delta G^0$, $\Delta H^0$, and $\Delta S^0$). Thermodynamic parameters are presented in Table 5. The first aspect is that adsorption was spontaneous, with the standard Gibbs free energy ranging from $-8.17$ to $-9.98$ kJ mol$^{-1}$.
Second, the adsorption process possesses exothermic nature, with the standard enthalpy variation of $-11.1519$ mol$^{-1}$. This value indicates that the interaction between the CV and OPBP is physical and occurs due to Van der Waals forces (Machado et al. 2011).

Mass transfer parameters

The estimated mass transfer parameters are exhibited in Table 6. To determine the dominant mechanism in the mass transport of the system CV/OPBP, it was used the Biot number (Eq. (33)):

$$Bi = \frac{k_f d_p C_0}{2 \rho D_s q_e}$$

Based on the low values of the Biot number ($Bi < 0.5$), it can be stated that the external mass transfer was more important than the intraparticle diffusion in the CV adsorption onto OPBP. This trend is not common in the liquid-phase adsorption systems, where, normally, the internal mechanisms are the limiting steps. However, some facts can be contributed for the behavior found in this work, as follows: the low particle size of the adsorbent, which in turn, provides a short diffusion path length, leading to a fast internal diffusion and the high value of external surface area (2068.9 cm$^2$ g$^{-1}$), which can have contributed to the attachment of a large number of CV molecules in the external surface of OPBP. Dotto et al. (2012) also pointed out that the external mass transfer mechanism was the most important in the tartrazine adsorption on chitin.

![Fig. 5 Isotherm curves of the CV adsorption on OPBP](image-url)

Table 3 Isotherm parameters for the CV adsorption onto OPBP

| Model      | Temperature (K) | 298   | 308   | 318   | 328   |
|------------|----------------|-------|-------|-------|-------|
| Langmuir   |                |       |       |       |       |
| $q_L$ (mg g$^{-1}$) | 272.09 | 347.83 | 391.22 | 444.34 |
| $K_L$ (L mg$^{-1}$) | 0.1016 | 0.0787 | 0.0754 | 0.0654 |
| $R^2$      | 0.9940         | 0.9959 | 0.9972 | 0.9970 |
| $R^2_{adj}$| 0.9915         | 0.9943 | 0.9960 | 0.9958 |
| ARE (%)    | 5.33           | 5.23  | 4.92  | 5.16  |
| MSE (mg g$^{-1}$)$^2$ | 69.96 | 74.30 | 63.47 | 81.68 |
| Freundlich |                |       |       |       |       |
| $K_F$ ((mg g$^{-1}$)(mg L$^{-1}$)$^{-1/2}$) | 87.35 | 90.48 | 94.30 | 95.09 |
| $1/n_F$ (dimensionless) | 4.79  | 3.99  | 3.74  | 3.43  |
| $R^2$      | 0.9446         | 0.9552 | 0.9540 | 0.9523 |
| $R^2_{adj}$| 0.9224         | 0.9373 | 0.9356 | 0.9333 |
| ARE (%)    | 15.14          | 16.24 | 17.70 | 18.44 |
| MSE (mg g$^{-1}$)$^2$ | 642.20 | 814.51 | 1032.33 | 310.50 |
| Sips       |                |       |       |       |       |
| $q_S$ (mg g$^{-1}$) | 262.52 | 335.42 | 373.63 | 415.30 |
| $K_S$ (mg L$^{-1}$) | 0.1176 | 0.0895 | 0.0875 | 0.0799 |
| $n_S$ (dimensionless) | 0.9900 | 0.9900 | 0.9900 | 0.9900 |
| $R^2$      | 0.9911         | 0.9936 | 0.9937 | 0.9905 |
| $R^2_{adj}$| 0.9844         | 0.9888 | 0.9889 | 0.9833 |
| ARE (%)    | 5.55           | 5.82  | 5.65  | 7.10  |
| MSE (mg g$^{-1}$)$^2$ | 124.26 | 139.56 | 170.71 | 310.50 |
Treatment of simulated effluents

The tests for the treatment of simulated effluents were done for two different compositions (Table 1), as previously mentioned. The adsorption tests were conducted in batch using 4.5 g L$^{-1}$ of OPBP, 150 rpm, 2 h, and room temperature. The solution UV-Vis spectra before and after the adsorption are presented in Fig. 6. By simple observation of Fig. 6, it can be seen the treatment efficiency, since the spectra were extremely amortized after the treatment. The absorbance values (areas under the curves) for the effluents A and B before the adsorption were 796.0 and 684.1 cm$^2$, respectively. After the adsorption, the areas diminished to 78.6 and 111.9 cm$^2$ for the effluents A and B. These values correspond to the removal of

### Table 4: Reported adsorption capacities for CV dye using different adsorbents

| Adsorbent                                      | pH  | $T$ (K) | $C_0$ (mg L$^{-1}$) | $q_m$ (mg g$^{-1}$) | Reference                  |
|-----------------------------------------------|-----|---------|---------------------|---------------------|----------------------------|
| OPBP                                          | 9   | 328     | 50-500              | 444.34              | This work                  |
| Graphene oxide intercalated montmorillonite nanocomposite | 6.2 | 303     | 50-200              | 746.27              | Puri and Sumana (2018)     |
| Date palm leaves                              | 10.1| 328     | 10-50               | 37.736              | Ghazali et al. (2018)      |
| Chitin nano-whiskers from shrimp shell         | 10  | 298     | 250                 | 39.56               | Gopi et al. (2016)         |
| Mango stone biocomposite                      | 8   | 306     | 100-400             | 352.79              | Shoukat et al. (2017)      |
| Biopolymers composites with peanut hull waste biomass | 8   | 323     | 25-200              | 100.6               | Tahir et al. (2017)        |
| Chitosan hydrogel beads                       | 7   | 303     | 10-60               | 76.9                | Pal et al. (2013)          |
| Coniferous pinus bark poder                   | 8   | 303     | 10-50               | 32.78               | Ahmad (2009)               |
| NaOH-modified rice hus                        | 8   | 273     | 20-100              | 44.87               | Chakraborty et al. (2011)  |
| Opal                                          | 7.4 | 303     | 20-150              | 101.13              | Ma et al. (2012)           |
| Grapefruit peel                               | 6   | 318     | 25-100              | 254.16              | Saeed et al. (2010)        |
| Terminalia arjuna sawdust waste               | 7   | 293     | 10-100              | 45.99               | Shakoor and Nasar (2018)   |
| Alginate-whey                                 | 6   | 313     | 50-350              | 220                 | Djelad et al. (2019)       |
| Magnetic biochar                              | 6   | 313     | 100-400             | 99.19               | Sun et al. (2015)          |
| Lignified elephant grass complexed isolate    | 7   | 343     | 10-50               | 5.06                | Aniagor and Menkiti (2018) |
| SnFe$_2$O$_4$@activated carbon magnetic nanocomposite | 8   | 323     | 25-100              | 158.73              | Rai et al. (2015)          |
| CoFe$_2$O$_4$/activated carbon magnetic       | 10.2| 303     | 100-300             | 184.2               | Liang et al. (2019)        |
| Clay/PNIPAm nanocomposite hydrogels           | 8.9 | 310     | 10-30               | 4.71                | Zhang et al. (2014)        |
| Jute fiber carbon                             | 8   | 303     | 20-80               | 27.99               | Porkodi and Vasanth Kumar (2007) |
| Formosa papaya seed powder                    | 8   | 298     | 5-1000              | 85.99               | Pavan et al. (2014)        |

### Table 5: Thermodynamic parameters for the CV adsorption onto OPBP

| $T$ (K) | $K_e$ (--) | $\Delta G^0$ (kJ mol$^{-1}$) | $\Delta H^0$ (kJ mol$^{-1}$) | $\Delta S^0$ (kJ mol$^{-1}$ K$^{-1}$) |
|---------|------------|-----------------------------|-----------------------------|--------------------------------------|
| 298     | 41,450.7   | $-26.3$                     | $-11.1$                     | 0.05                                 |
| 308     | 32,107.9   | $-26.6$                     |                             |                                      |
| 318     | 30,761.6   | $-7.3$                      |                             |                                      |
| 328     | 26,681.8   | $-27.8$                     |                             |                                      |

### Table 6: Mass transfer parameters for the CV adsorption onto OPBP

| $C_0$ (mg L$^{-1}$) | $C_e$ (mg L$^{-1}$) | $k_L$ (cm$^3$ mg$^{-1}$ s$^{-1}$) | $k_f$ ($10^4$ cm$^3$ s$^{-1}$) | $D_p$ (cm$^2$ s$^{-1}$) | $D_S$ (cm$^2$ s$^{-1}$) | Bi (--) |
|---------------------|---------------------|---------------------------------|-------------------------------|------------------------|------------------------|---------|
| 50                  | 3.27                | $1.87 \times 10^{-4}$          | 5.26                          | $1.80 \times 10^{-8}$ | $8.01 \times 10^{-8}$ | 2.55 $10^{-1}$ |
| 100                 | 13.67               | $6.07 \times 10^{-5}$          | 4.82                          | $4.62 \times 10^{-6}$ | $3.73 \times 10^{-3}$ |         |
| 150                 | 48.74               | $3.62 \times 10^{-5}$          | 3.79                          | $1.27 \times 10^{-5}$ | $1.36 \times 10^{-3}$ |         |
| 250                 | 110.00              | $3.66 \times 10^{-5}$          | 3.69                          | $1.93 \times 10^{-5}$ | $1.05 \times 10^{-4}$ |         |
The OPBP is composed of particles with the surface presenting a honeycomb pattern. Being mainly constituted of organic functional groups presented on the amorphous phase. The functional groups presented on the amorphous phase. The OPBP is composed of particles with the surface present-ing a honeycomb pattern. Being mainly constituted of organic

Thermodynamic parameters shown that the adsorption process is spontaneous, exothermic, and probably due to Van der Waals forces. The Biot number (0.0011 ≤ Bi ≤ 0.25) indicates that the external mass transfer is controlling the adsorption process of the CV onto the OPBP. Lastly, the adsorbent can be used as an effective adsorbent to polish textile effluents with different compositions, attaining color removal efficiency around 90%.

**List of symbols**

- $c_e$, initial CV concentration in bulk solution (mg L$^{-1}$);
- $c_{e,e}$, predicted equilibrium concentration by pseudo-first-order model (mg L$^{-1}$);
- $c_{e,2}$, predicted equilibrium concentration by the pseudo-second order (mg L$^{-1}$);
- $c_{e,Av}$, predicted equilibrium concentration by the Avrami model (mg L$^{-1}$);
- $c_{e,n}$, predicted equilibrium concentration by the general-order model (mg L$^{-1}$);
- $c_{e,CV}$, CV concentration in bulk solution at any time (mg L$^{-1}$);
- $D_{AB}$, CV diffusion coefficient at infinite dilution (cm$^2$ s$^{-1}$);
- $D_m$, mass of adsorbent per volume of solution (g L$^{-1}$);
- $D_p$, effective pore volume diffusion coefficient (cm$^2$ s$^{-1}$);
- $D_{sb}$, surface diffusion coefficient (cm$^2$ s$^{-1}$);
- $k_1$, kinetic constant for the pseudo-first order (min$^{-1}$);
- $k_2$, kinetic constant for the pseudo-second order (mg g$^{-1}$ min$^{-1}$);
- $k_A$, kinetic constant for the Avrami model (min$^{-1}$);
- $K_w$, equilibrium constant, dimensionless;
- $K_f$, Freundlich parameter (mg$^2$ L$^{-1}$ mg$^{-1}$);
- $K_L$, Langmuir parameter (L mg$^{-1}$);
- $k_{Loc}$, kinetic constant for the Loebenstein model (mg$^{-1}$ min$^{-1}$);
- $k_{f,1}$, kinetic constant for the general rate order (min$^{-1}$ mg$^{-1}$ g$^{-1}$);
- $K_{Sips}$, Sips parameter (L mg$^{-1}$ g$^{-1}$);
- $K_{WB}$, kinetic constant of the Weber-Miller model (L mg$^{-1}$ min$^{-1}$);
- $M_w$, molar mass of water (g mol$^{-1}$);
- $nf$, heterogeneity factor, dimensionless;
- $N_p$, number of transfer units for external mass transfer (s$^{-1}$);
- $N_{ntu}$, number of transfer unit for internal mass transfer (s$^{-1}$);
- $N_{su}$, number of transfer units for lumped kinetics, dimensionless;
- $N_{tpu}$, number of transfer units for pore diffusion (s$^{-1}$);
- $N_{spu}$, number of transfer units for the surface diffusion (s$^{-1}$);
- $q_{te}$, mass of CV adsorbed at the equilibrium (mg g$^{-1}$);
- $q_{texp}$, experimental mass of CV adsorbed per gram of adsorbent at any time (mg g$^{-1}$);
- ARE, average relative error (%);
- $d_{ap}$, average adsorbent diameter (μm);
- $K_{Loe}$, kinetic constant for the Loebenstein model (mg L$^{-1}$ min$^{-1}$);
- $K_{WB}$, molar mass of CV (g mol$^{-1}$);
- $n$, number of experimental values, dimensionless;
- $p$, number of parameters of the model;
- $R$, universal gas constant (8.31 × 10$^{-3}$ kJ mol$^{-1}$ K$^{-1}$); $R^2$, determination coefficient, dimensionless;
- $R^2_{adj}$, adjusted determination coefficient, dimensionless;
- $S$, external surface area per mass of adsorbent (cm$^2$ g$^{-1}$); SSE, sum of squared errors;
- $T$, temperature of the solution (K);
- $V$, solution volume (L);
- $V_{m}$, molar volume of CV (cm$^3$ mol$^{-1}$); $V_{p}$, pore volume of adsorbent (cm$^3$ g$^{-1}$);
- $x$, association parameter of water, dimensionless;
- $y_{exp}$, experimental data; $y_{pred}$, predicted data

**Greek letters**

- $\alpha$, initial adsorption rate for the Elovich model (mg g$^{-1}$ min$^{-1}$);
- $\beta$, desorption constant for the Elovich model (mg g$^{-1}$);
- $\gamma$, unitary activity coefficient of CV (1 mol L$^{-1}$);
- $f^S$, activity coefficient of CV in solution, 1 dimensionless;
- $\gamma$, void fraction, dimensionless;
- $\Delta G^0$, standard Gibbs free energy change (kJ mol$^{-1}$);
- $\Delta H^f$, standard enthalpy change (kJ mol$^{-1}$);
- $\Delta S^0$, standard entropy change (kJ mol$^{-1}$ K$^{-1}$);
- $\eta$, Weber-Miller constant (mg L$^{-1}$ min$^{-1}$);
- $\phi_{aw}$, water viscosity (cp);
- $\omega$, Weber-Miller constant (mg L$^{-1}$);
- $\rho_{d}$, apparent density of the adsorbent (g L$^{-1}$);
- $\rho_a$, density of the adsorbent (g L$^{-1}$);
- $\tau$, tortuosity factor, dimensionless;
- $\omega$, Loebenstein constant, dimensionless

**References**

Afrozse S, Sen TK, Ang HM (2016) Adsorption removal of zinc (II) from aqueous phase by raw and base modified Eucalyptus sheathiana
bark: kinetics, mechanism and equilibrium study. Process Saf Environ Prot 102:336-352
Ahmad R (2009) Studies on adsorption of crystal violet dye from aqueous solution onto coniferous pine bark powder (CPBP). J Hazard Mater 171:767-773
Anbia M, Salehi S (2012) Removal of acid dyes from aqueous media by adsorption onto amino-functionalized nanoporous silica SBA-3. Dyes Pigments 94:1-9
Aniagor CO, Menkiti MC (2018) Kinetics and mechanistic description of adsorpive uptake of crystal violet dye by lignified elephant grass complexed isolate. J Environ Chem Eng 6:2103-2118
Avnami M (1939) Kinetics of phase change. I. General theory. J Chem Phys 7:1105-1112
Bairagi H, Khan MMR, Ray L, Guha AK (2011) Adsorption profile of lead on Aspergillus versicolor: a mechanistic probing. J Hazard Mater 186:756-764
Bonilla-Petriciolet A, Mendoza-Castillo DI, Reynel-Ávila HE (2017) Kinetics and mechanism of alginate-whey an effective and green adsorbent for crystal violet adsorption onto chitin and chitosan. Ind Eng Chem Res 56:6862-6868
Elvich SY, Larinov OG (1962) Theory of adsorption from solutions of non-electrolytes on solid (I) equation adsorption from solutions and the analysis of its simplest form, (II) verification of the equation of adsorption isotherm from solutions. Izv Akad Nauk SSSR Otd Khim Nauk 2:209-216
Essawy AA, Ali AEH, Abdel-Mottaleb MSA (2008) Application of novel copolymer-TiO2 membranes for some textile dyes adsorptive removal from aqueous solution and photocatalytic decolorization. J Hazard Mater 157:547-552
Djelad A, Mokhtar A, Khelifa A, Bengueddach A, Sassi M (2019) Alginate-whey an effective and green adsorbent for crystal violet removal: kinetic, thermodynamic and mechanism studies. Int J Biol Macromol 139:944-954
Dotto GL, Vieira MLG, Pinto LAA (2012) Kinetics and mechanism of tartrazine adsorption onto chitin and chitosan. Ind Eng Chem Res 51:8662-8668
Georgin J, Marques BS, Peres EC, Allasia D,Dotto GL (2018) Biosorption of cationic dyes by Pará chestnut husk (Cedrella fissilis) based on biomass (2012) Antinociceptive effects of a chloroform extract and the alkaloid dicentrine isolated from fruits of Ocotea puberula). Water Sci Technol 78:1543-1548
Langerren S (1898) About the theory of so-called adsorption of soluble substances. Kung Svenska Vetenskap 24:1-39
Ma W, Song X, Pan Y, Cheng Z, Xin G, Wang B, Wang X (2012) Adsorption behavior of crystal violet onto opal and reuse feasibility of opal-dye sludge for binding heavy metals from aqueous solutions. Chem Eng J 193-194:381-390
Machado FM, Bergmann CP, Fernandes THM, Lima EC, Royer B, Calveté T, Fagan SB (2011) Adsorption of reactive red M-2BE dye from water solutions by multi-walled carbon nanotubes and activated carbon. J Hazard Mater 192:1122-1131
Martínez M, Miralles N, Hidalgo S, Núñez, Villaescusa I, Poch J (2006) Removal of lead (II) and cadmium (II) from aqueous solutions using grape stalk waste. J Hazard Mater 133:203-211
Muntroncchio D, Miguel O, Zanin S, da Silva G, Cardozo A, Santos A (2012) Antinociceptive effects of a chloroform extract and the alkaloid dicentrine isolated from fruits of Ocotea puberula. Med Plant 78:1543-1548
Pal A, Pan S, Saha S (2013) Synergistically improved adsorption of anionic surfactant and crystal violet on chitosan hydrogel beads. Chem Eng J 217:426-434
Pavan FA, Camacho ES, Lima EC, Dotto GL, Branco VTA, Dias SLP (2014) Formospora papaya seed powder (FPSP): preparation, characterization and application as an alternative adsorbent for the removal of crystal violet from aquatic phase. J Environ Chem Eng 2:230-238
Porkodi K, Vasanth Kumar K (2007) Equilibrium, kinetics and mechanism modeling and simulation of basic and acid dyes sorption onto jute fiber carbon: eosin yellow, malachite green and crystal violet single component systems. J Hazard Mater 143:311-327
Puri C, Sumana G (2018) Highly effective adsorption of crystal violet dye from contaminated water using graphene oxide intercalated montmorillonite nanocomposite. Appl Clay Sci 166:102-112
Qureshi K, Ahmad MZ, Bhatti IA, Iqbal M, Khan A (2015) Cytotoxicity reduction of wastewater treated by advanced oxidation process. Chem Int 1:53-59
Rai P, Gautam RK, Banerjee S, Rawat V, Chattopadhyaya MC (2015) Synthesis and characterization of a novel SnFe$_2$O$_4$@activated carbon magnetic nanocomposite and its effectiveness in the removal of crystal violet from aqueous solution. J Environ Chem Eng 3: 2281-2291

Saeed A, Sharif M, Iqbal M (2010) Application potential of grapefruit peel as dye sorbent: kinetics, equilibrium and mechanism of crystal violet adsorption. J Hazard Mater 179:564-572

Sarma GK, Sen Gupta S, Bhattacharyya KG (2016) Adsorption of crystal violet on raw and acid-treated montmorillonite, K10, in aqueous suspension. J Environ Manag 171:1-10

Sartape AS, Mandhare AM, Jadhav VV, Raut PD, Anuse MA, Kolekar SS (2017) Removal of malachite green dye from aqueous solution with adsorption technique using Limonia acidissima (wood apple) shell as low cost adsorbent. Arab J Chem 10:S3229-S3238

Schadeck Netto M, da Silva NF, Mallmann ES et al (2019) Effect of salinity on the adsorption behavior of methylene blue onto comminuted raw avocado residue: CCD-RSM design. Water Air Soil Pollut:230. https://doi.org/10.1007/s11270-019-4230-x

Shakoor S, Nasar A (2018) Adsorptive decontamination of synthetic wastewater containing crystal violet dye by employing Terminalia arjuna sawdust waste. Groundw Sust Dev 7:30-38

Shoukat S, Bhatti HN, Iqbal M, Nooreen S (2017) Mango stone biocomposite preparation and application for crystal violet adsorption: a mechanistic study. Microporous Mesoporous Mater 239:180-189

Silva JS, Rosa MP, Beck PH, Peres EC, Dotto GL, Kessler F, Grasel FS (2018) Preparation of an alternative adsorbent from Acacia Mearnsii wastes through acetosolv method and its application for dye removal. J Clean Prod 180:386-394

Sips RJ (1948) On the structure of a catalyst surface. J Chem Phys 16: 490-495

Sun P, Hui C, Azim Khan R, Du J, Zhang Q, Zhao YH (2015) Efficient removal of crystal violet using Fe3O4-coated biochar: the role of the Fe$_2$O$_3$ nanoparticles and modeling study their adsorption behavior. Sci Rep 5

Tahir M, Bhatti HN, Iqbal M (2016) Solar red and brittle blue direct dyes adsorption onto Eucalyptus angopheroides bark: equilibrium, kinetics and thermodynamic studies. J Environ Chem Eng 4:2431-2439

Tahir N, Bhatti HN, Iqbal M, Nooreen S (2017) Biopolymers composites with peanut hull waste biomass and application for crystal violet adsorption. Int J Biol Macromol 94:210-220

Uddin MT, Rahman MA, Rukanuzzaman M, Islam MA (2017) A potential low cost adsorbent for the removal of cationic dyes from aqueous solutions. Appl Water Sci 7:2831-2842

Vuono D, Catizzone E, Aloise A, Policicchio A, Agostino RG, Migliori M, Giordano G (2017) Modelling of adsorption of textile dyes over multi-walled carbon nanotubes: equilibrium and kinetic. Chin J Chem Eng 25:523-532

Wang H, Yao Q, Wang C et al (2016) A simple, one-step hydrothermal approach to durable and robust superparamagnetic, superhydrophobic and electromagnetic wave-absorbing wood. Sci Rep 6:2-11

Weber WJ, Miller CT (1988) Modelling the sorption of hydrophobic contaminants by aquifer materials-I: rates and equilibria. Water Res 22:457-464

Weber CT, Folletto EL, Meili L (2013) Removal of tannery dye from aqueous solution using papaya seed as an efficient natural biosorbent. Water Air Soil Pollut:224. https://doi.org/10.1007/s11270-012-1427-7

Weber CT, Collazzo GC, Mazutti MA, Folletto EL, Dotto GL (2014) Removal of hazardous pharmaceutical dyes by adsorption onto papaya seeds. Water Sci Technol 70:102-107. https://doi.org/10.2166/wst.2014.200

Wilke CR, Chang P (1955) Correlation of diffusion coefficients in dilute solutions. AIChE J 1:264-268

Xu Z, Wang Q, Jiang Z, Yang X, JI Y (2007) Enzymatic hydrolysis of pretreated soybean straw. Biomass Bioenergy 31:162-167

Yuan G, Zhao B, Chu KH (2020) Adsorption of fluoride by porous adsorbents: estimating pore diffusion coefficients from batch kinetic data. Environ Eng Res 25:645-651. https://doi.org/10.4491/eer.2019.205

Zangaro W, Nisizaki SMA, Domingos JCB, Nakano EM (2003) Mycorrhizal response and successional status in 80 woody species from southern Brazil. J Trop Ecol 19:315-324

Zhang Q, Zhang T, He T, Chen L (2014) Removal of crystal violet by clay/PNIPAm nanocomposite hydrogels with various clay contents. Appl Clay Sci 90:1-5

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