Prickly pear cactus cladodes powder of *Opuntia ficus indica* as a cost effective biosorbent for dyes removal from aqueous solutions

Ibtihel Louati¹ · Mariem Fersi² · Bilel Hadrich² · Bouthaina Ghariani¹ · Moncef Nasri¹ · Tahar Mechichi¹

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Abstract

The textiles manufacturing is one of the core industries that release a huge amount of dyes during the dyeing process. As a result, the growing demand of an efficient and low-cost treatment has given rise to alternative adsorbents. In the present study, prickly pear cactus cladodes powder (PPCP) of *Opuntia ficus indica* was investigated as an ecofriendly and low-cost biosorbent of Acid orange 51 (AO51) and Reactive Red 75 (RR75) dyes commonly used in dyeing. The FTIR spectroscopic characterization of PPCP showed the heterogeneity in surface structure and functional groups which confers to the biosorbent its capability to interact with acidic (AO51) and reactive (RR75) dyes molecules. Effects of pH, temperature, initial dye concentration and adsorbent dose on adsorption yield were investigated. The dyes uptake process was closely fitted to the pseudo-second order kinetic for both dyes. Experimental data were analyzed by applying the Langmuir, Freundlich, Dubinin–Raduskevich, Temkin, Redlich–Peterson, and BET isotherms equations. The models of BET and Langmuir were considered as the best isotherms models fitting experimental data, respectively, of RR75 and AO51. The maximum Langmuir monolayer biosorption capacities were of 198.9 and 45 mg g⁻¹, respectively for RR75 and AO51.

Keywords Prickly pear cactus · Powder · Dyes · Biosorption · Kinetics · Isotherms

Abbreviations

C (mg L ⁻¹)	Dye concentration
q (mg g ⁻¹)	Quantity of dye biosorbed per unit mass of biosorbent
r (g L ⁻¹)	Mass of biosorbent per liter of aqueous solution
R	Gas constant (8.314 J mol ⁻¹ K)
T	Absolute temperature (K)

Subscripts

0	Initial
eq	Equilibrium
m	Maximum
mono	Monolayer

Introduction

The textile industry plays an important role in the world's economy as well as in the daily life, but at the same time it discharges huge quantities of polluted wastewaters (Kant 2012; Bhatia et al. 2018). The major chemical pollutants present in textile wastewater are dyes, which are considered as one of the biggest threats to global aquatic resources. Today, about 100,000 synthetic dyes are commercially available and nearly 1 million tons of dyes are produced per year. Whereas, out of the total usage, 10% of dyes are released in nature as dyestuff waste (Selvam et al. 2003). Most of these dyes are highly toxic, mutagenic, carcinogenic and difficult to biodegrade due to their complex aromatic molecular structure (Alqaragully 2014; Senthil kumar et al. 2011; Rawat et al. 2016). It has already been demonstrated that they strongly affect the photosynthetic activities, aquatic biota growth and gas solubility in water bodies (Jain and Sikarwar 2008). Hence, ecofriendly removal of such contaminants in wastewaters becomes a necessity. In this concern, industries are more and more stressed by environmental legislations becoming stricter in effluents discharge instructions (Hessel et al. 2007). Fortunately, there is no single way to overcome this problem, a variety of dye removal technologies has been investigated and these include biological (biosorption,

✉ Tahar Mechichi
tahar.mechichi@enis.rnu.tn

¹ Laboratory of Enzyme Engineering and Microbiology, National School of Engineers of Sfax, University of Sfax, BP 1173, 3038 Sfax, Tunisia

² Unité de Biotechnologie des Algues, Biological Engineering Department, National School of Engineers of Sfax, University of Sfax, Sfax, Tunisia

bioaccumulation and biodegradation), chemical (electrocoagulation, electrochemical oxidation, photocatalytic degradation, etc.), and physical (membrane filtration, precipitation, adsorption, coagulation, flocculation, etc.) treatments. Among all these methods, adsorption is found to be the most efficient in dye elimination especially if the sorbent is a low-cost material and does not require any additional pretreatments before its use (Karthik et al. 2014; Gupta and Suhas 2009). At present, there is a growing interest in using natural biomaterials instead of conventional sorbents. Several studies investigated the potential of low-cost adsorbents such as pumpkin seed powder (Subbaiah and Kim 2016), peanut shell (Abbas et al. 2012), red and yellow clay (Aziz 2013), corn straw (Umpuch and Jutarat 2013), red mud (Nadaroglu et al. 2010), wheat bran (Yao et al. 2012), *Enteromorpha prolifera* (Sun et al. 2013), citrus peels (Njikam and Schiewer 2012), banana peels (Annadurai et al. 2002), pine sawdust (Özacar and Şengil 2005), rice husk (McKay et al. 1999) and waste from fruits of *Eugenia umbelliflora* berg (Postai and Rodrigues 2018).

The prickly pear cactus (*Opuntia ficus indica*) grows in all the semi-arid countries throughout the world and, is especially cultivated in the Mediterranean region and in Central America. The use of this biomaterial could be a promising alternative due to its relative abundance, low-cost, effectiveness and ecofriendly nature. Recently, several studies assessed the potential of dried prickly pear cactus cladodes powder (PPCP) for micro-pollutants removal from wastewater. Barka et al. (2013a, b) reported its effectiveness in heavy metals (cadmium and lead) and synthetic dyes (Methylene Blue, Eriochrome Black T and Alizarin S) removal from aqueous solutions. Peláez-Cid et al. (2013) used (*Opuntia ficus indica*) fruit wastes in its untreated and activated forms as adsorbent for basic and reactive textile dyes.

The main objective of this study is to investigate the potential of dried prickly pear cactus cladodes as a low-cost, natural and ecofriendly biosorbent of two synthetic dyes belonging to two different families: Acid Orange 51 (AO51) and Reactive Red (RR75). The adsorption treatment was chosen due to its flexibility, simplicity of industrial design, low initial cost and ease of operation. The characterization of the used adsorbent was carried out using FTIR and SEM analysis. The influence of experimental parameters such as

pH, contact time, temperature, dye and sorbent concentrations, on dyes adsorption were investigated. Adsorption kinetics as well as equilibrium data were also analyzed. This study provides the insight into potential of industrial application of PPCP as a widely available biomaterial for adsorptive dye removal from aqueous solutions.

Materials and methods

Adsorbent

The prickly pear cladodes powder (PPCP) used in this study was generously provided by a local company located in Kasserine (Tunisia) specialized in the production and the export of organic cactus pear *Opuntia ficus indica*. The prickly pear cladodes, collected in February, were dried at low temperature then powdered into very fine particles. The powder was used without any pre-treatment.

Adsorbates

Acid Orange 51 (AO51) and Reactive Red (RR75) were obtained from Sigma-Aldrich. Their identification information's and molecular structures are depicted in Table 1. Stock solutions were prepared by dissolving 5 g L⁻¹ of each dye in distilled water, and the work concentrations were obtained by dilution of the stock solutions.

Adsorption experiments

Biosorption assays were conducted in 50 mL-flasks by varying sorbent concentration (10–100 g L⁻¹), dyes concentrations (25–1000 mg L⁻¹), pH (2–12), temperature (20–60 °C) and incubation time (0–120 min) at constant speed stirring (150 rpm). The pH values of solutions were adjusted using 0.1 M HCl and 0.1 M NaOH solutions. The concentration of remaining dyes in the adsorption medium was determined, during the experiment, by measuring the optical density at 446 and 520, respectively, corresponding to AO51 and RR75 $\lambda_{\max}$, by an UV/Vis spectrophotometer. The biosorption yield was calculated using the following equations. Equation (1) was

Table 1 Physicochemical characteristics of AO51 and RR75

Name	Molecular structure	M_w (g mol ⁻¹)	$\lambda_{\max}$ (nm)
Acid Orange 51 (AO51)		860.81	446
Reactive Red 75 (RR75)		990.79	520

used for biosorption kinetics experiments and Eq. (2) was used for biosorption isotherms ones:

$$\text{Biosorption \%} = \frac{(C_0 - C_{\text{eq}})}{C_0} * 100 \quad (1)$$

$$q_{\text{eq}} = \frac{(C_0 - C_{\text{eq}})}{r} \quad (2)$$

PPCP characterization

FTIR spectra of PPCP in the range of 600–4000 cm^{-1} were used to identify functional groups responsible for the color binding using an Agilent Cary 130 FTIR spectrophotometer. PPCP surface morphology was evaluated using scanning electron microscope JEOL (JFC-1100E) using an accelerating voltage of 15 kV. To create a conductive layer of metal, PPCP sample was gold coated before examination in the SEM. The average size of PPCP particles was measured by the mean of the Laser Particle Sizer (LPS) ANALYSETTE 22 NanoTec.

Modeling of adsorption kinetics

Several models could be used to investigate the adsorption process. Pseudo-first order, pseudo-second order, intra-particle diffusion and Elovich models were used to fit the experimental data. The pseudo-first order model equation proposed by Lagergren (1898) is expressed as follows:

$$\frac{dq}{dt} = k_1 \cdot (q_{\text{eq}} - q) \quad (3)$$

After integrating by applying the boundary conditions ($q=0$ at $t=0$ and $q=q$ at $t=t$), the following equation can be obtained:

$$q = q_{\text{eq}} \cdot (1 - e^{-k_1 \cdot t}) \quad (4)$$

where k_1 (min^{-1}) is the adsorption rate constant.

The pseudo-second order model described by Ho and McKay (1999) assumes that the adsorption follows second order chemisorption. This model was used to explain the sorption kinetics by the following expression:

$$\frac{dq}{dt} = k_2 \cdot (q_{\text{eq}} - q)^2 \quad (5)$$

After integrating with the same boundary conditions, the Eq. (5) becomes:

$$q = \frac{k_2 \cdot q_{\text{eq}}^2 \cdot t}{1 + k_2 \cdot q_{\text{eq}} \cdot t} \quad (6)$$

where k_2 ($\text{g mg}^{-1} \text{min}$) is the adsorption rate constant of the pseudo-second order adsorption.

The experimental kinetic results were also analyzed by the intra-particle diffusion model (Weber and Morris 1963) to elucidate the dyes diffusion mechanism into the PPCP which equation is given as:

$$q = k_p \cdot t^{\frac{1}{2} + C}, \quad (7)$$

where C is the intercept. k_p is the intra-particle diffusion rate constant ($\text{mg g}^{-1} \text{min}^{-1/2}$).

The Elovich model is one of the most used models to describe chemisorption of a substrate into a solid surface without product desorption (Low 1960). In this reaction, adsorption yield decreases with time due to the surface coverage increase. The Elovich model is generally described by the following expression:

$$\frac{dq}{dt} = \alpha \cdot \exp(-\beta q), \quad (8)$$

where α is the initial adsorption rate ($\text{mg g}^{-1} \text{min}^{-1}$), β is the desorption constant (g mg^{-1}).

Modelling of adsorption isotherms

Equilibrium adsorption isotherm of RR75 and AO51 on PPCP were analyzed using both two (Langmuir, Freundlich, Dubinin-Raduskevich and Temkin) and three (Redlich–Peterson and BET) parameter models.

Langmuir model

Irving Langmuir (1918) proposed a model isotherm for gases adsorbed into solids, which explains adsorption by considering that an adsorbate behaves as an ideal gas at isothermal conditions. Langmuir proposed his theory by making the following assumptions:

1. The surface of the adsorbent is uniform, that is, all the vacant sites are of equal size and shape on the surface of adsorbent.
2. Adsorbed molecules do not interact.
3. All adsorption occurs through the same mechanism and a constant amount of heat energy is released during this process.
4. At the maximum adsorption, only a monolayer is formed.

The Langmuir equation is:

$$q_{\text{eq}} = \frac{q_m \cdot K_L \cdot C_{\text{eq}}}{1 + K_L \cdot C_{\text{eq}}}, \quad (9)$$

where K_L is the Langmuir equilibrium constant (L mg^{-1}).

Freundlich model

The Freundlich model is applied to describe adsorption on heterogeneous sorbent surfaces and the interaction between adsorbed molecules. Application of the Freundlich isotherm suggests that adsorption energy exponentially decreases (Sheindorf et al. 1981). This isotherm model is empirical and can be employed to describe multilayer sorption as shown in the following expression:

$$q_{\text{eq}} = K_F \cdot C_e^{1/n}, \quad (10)$$

where K_F is the Freundlich constant describing the sorbent adsorption capacity ($\text{mg}^{1-1/n} \text{g}^{-1} \text{L}^{1/n}$). n is the heterogeneity factor related to the adsorption intensity.

Temkin model

Temkin isotherm takes account of the effect of some indirect adsorbate/adsorbate interactions and suggests that the adsorption heat of all the molecules in the layer would linearly decrease with coverage (Temkin and Pyzhev 1940). It has been generally applied in the following form:

$$q_{\text{eq}} = \frac{RT}{b} \cdot \ln(A \cdot C_{\text{eq}}), \quad (11)$$

where b is the Temkin constant related to heat of sorption (J mol^{-1}). A is the Temkin isotherm constant (L/g).

Dubinin–Raduskevich model

This model was applied to determine if the adsorption occurred by a physical or chemical process (Dubinin and Radushkevich 1947). The D–R equation is described as follows:

$$q_{\text{eq}} = q_m \cdot \exp(-k \cdot \varepsilon^2), \quad (12)$$

where k is a constant related to the adsorption energy ($\text{mol}^2 \text{kJ}^{-2}$). ε is the Polanyi potential calculated from the following equation:

$$\varepsilon = R \cdot T \cdot \ln\left(1 + \frac{1}{C_{\text{eq}}}\right) \quad (13)$$

Redlich–Peterson model

The Redlich–Peterson model is a combination of both Langmuir and Freundlich equations into a single one. It proposed an empirical equation which may be used to represent adsorption equilibrium over a wide concentration range in

either heterogeneous or homogenous systems (Redlich and Peterson 1959). At low surface coverage, the Redlich–Peterson equation reduces to the Freundlich isotherm at high adsorbate concentration, and to the Langmuir isotherm when $\beta = 1$. The equation is given as:

$$q_{\text{eq}} = \frac{K_R \cdot C_{\text{eq}}}{1 + \alpha_R \cdot C_{\text{eq}}^\beta}, \quad (14)$$

where K_R is the Redlich–Peterson isotherm constant (L g^{-1}), α_R is Redlich–Peterson isotherm constant (L mg^{-1}), β is the exponent which lies between 0 and 1.

BET model

The BET model (Brunauer et al. 1938) is an extension of the Langmuir theory, considering only monolayer adsorption, to multilayer adsorption based on the following hypothesis:

1. Adsorption is multilayer
2. No interaction between adsorption layer
3. Langmuir model can be applied to each layer

The BET equation is expressed as follows:

$$q_{\text{eq}} = \frac{a \cdot q_{\text{mono}} \cdot C_{\text{eq}}}{(C - C_{\text{eq}}) \cdot \left(1 + (a - 1) \cdot \frac{C_{\text{eq}}}{C}\right)}, \quad (15)$$

where q_{mono} is the dye amount required to saturate a monolayer (mg g^{-1}), a is a thermodynamic constant, C is the dye concentration required to saturate the system (mg L^{-1}).

Statistical analysis

Kinetics and isotherms models fitting as well as parameters estimation of each model was carried out with non-linear regression method using Matlab R2010a (The MathWorks, USA) software. The quality of each models' fitting has been tested by calculating the coefficient of determination (R^2), the adjusted coefficient of determination (R^2_{adj}), the root mean squared error (RMSE) and the sum of squared error of prediction (SSE), described in the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y}_i)^2} \quad (16)$$

$$R^2_{\text{adj}} = 1 - (1 - R^2) \cdot \frac{n-1}{n-p} \quad (17)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{n - p}} \quad (18)$$

$$\text{SSE} = \sum_{i=1}^n (Y_i - \hat{Y}_i)^2 \quad (19)$$

with Y_i : experimental value; $\hat{Y}_i$: calculated value; $\bar{Y}_i$: arithmetic mean of all experimental values; n : number of experimental values; p : number of model parameters.

The best model was chosen from the comparison between the four previously defined statistical criteria.

Results and discussion

Biosorbent characterization

FTIR spectra in the range of 600–4000 cm^{-1} of PPCP were analyzed to identify the nature of functional groups at the biosorbent surface that could be responsible for dyes binding. Figure 1 shows a band at 3235 cm^{-1} which may be assigned to the O–H stretching vibration of carboxylic acids. The band at 2916 cm^{-1} was due the asymmetric CH_2 stretching vibrational frequencies $[(\text{CH}_2)]$ and (CH_2) . The peak located at 1718 cm^{-1} was an indication of stretching vibration of C=O groups of ketones, aldehydes and carboxylic acids. The band at 1602 cm^{-1} is attributed to the stretching vibration of the C=C groups of cyclic alkenes. The sharp peak at 1420 cm^{-1} is corresponding to carboxylic acids and alcohols –OH bending. The peak observed at 1313 cm^{-1} reflects the vibration of O–H groups of phenols. The band at 1013 cm^{-1} is due to the C–O stretching vibration of esters. Peak at 779 could be explained by the presence of

Fig. 1 FTIR spectra of dried prickly pear cactus cladodes powder

C–H groups of aromatic compounds. These spectra indicate that the studied biomaterial contains a variety of functional groups such as carboxyl, hydroxyl, aldehydes, ketones and esters suggesting that it be used as an alternative for dyes removal (Barka et al. 2013a, b; Peláez-Cid et al. 2013; Subbaiah and Kim 2016). SEM micrographs of PPCP illustrated in Fig. 2 show that the powder was an agglomerate of fine particles with irregular and broken edges. Particles were of different shape and size. The PPCP particle size shows that the grain size distribution of the studied PPCP can be grouped as Normal-Gaussian particle size distribution. Globally, particles dimensions ranged from 10 to 300 μm in which more than 80% of the particles are grouped in the region of 100–120 μm .

Effect of adsorbent dose

The effect of biosorbent concentration on dye decolorization was tested at concentrations ranging from 0 to

Fig. 2 SEM analysis of dried prickly pear cactus cladodes powder

Fig. 3 Effect of PPCP concentration on RR75 and AO51 biosorption. Initial dyes concentration = 100 mg L^{-1} ; Incubation time = 30 min; temperature = 30 $^{\circ}\text{C}$; agitation = 150 rpm

120 g L⁻¹. Figure 3 shows that for both dyes RR75 and AO51, increasing biosorbent concentration in the range of 0–20 mg L⁻¹, resulted in a sharp increase in the biosorption yield. This enhancement in biosorption yield could be due to an increase in the number of possible dye binding sites and the biosorbent surface area (Chowdhury et al. 2011). However, an increase in biomass dosage over than 20 g L⁻¹ did not improve the biosorption yield. This finding could be explained by the complete adsorption of the dye at 20 mg L⁻¹. Similar behavior was described by Barka et al. (2013a, b) and Sakr et al. (2015). By the other hand, AO51 dye presented a maximal adsorption yield for 10 g L⁻¹ biosorbent dosage. Over this amount, a slight decrease in biosorption yield was observed, this can be explained by the eventual congestion caused by the increase in biosorbent dosage, which make more difficult the binding of dye molecules (Sakr et al. 2015). With the increase in adsorbent dosage aggregation of particles take place, and number of active sites in the dyes molecules is more and more limited. This is also depending on the AO51 spatial structure, which is also a crucial parameter in dye binding. According to (Donia et al. 2009), the quasi-planar configuration of some dyes such as in case of AO12 facilitates their interaction with the sorbent surface. This type of interaction leads to a large number of hidden active sites on the surface thing, which limits the interaction with dye molecules. The twisted structure in other case of dyes such as AO10 interacts through the negatively charged sulfonate groups giving strong interaction as well as more active sites available for interaction with the dye.

Effect of pH

One of the main parameters affecting the adsorption process is pH, influencing both dye solubility and biosorbent surface charge. The removal of RR75 and AO51 by PPCP

Fig. 4 Effect of pH on RR75 and AO51 biosorption (biosorbent concentration = 20 g L⁻¹ for RR75 and 10 g L⁻¹ for AO51; dye concentration = 100 mg L⁻¹; incubation time = 30 min; temperature = 30 °C; agitation = 150 rpm)

was studied at 30 °C, 20 g L⁻¹ (for RR75) and 10 g L⁻¹ (for AO51) biosorbent amount and 100 mg L⁻¹ dye concentration by varying the pH from 2 to 12. Figure 4 shows that RR75 removal from aqueous solution was strongly affected by the pH medium variation while AO51 adsorption efficiency was not. The results indicate that PPCP presented better removal capacity in acidic medium than in basic one for RR75 dye. The biosorption capacity progressively decreased from 94% to 43% when the pH solution was increased from 2 to 10. At pH 12, an increase in the biosorption yield was observed (63%). At low pH, the increase in H⁺ ion concentration leads to the acquirement of positive charges at the PPCP surface, so significant electrostatic attraction appears between the positively charged PPCP surface and the negatively charged SO₃⁻ dyes anion (Barka et al. 2013b; El Haddad et al. 2013; Subbaiah and Kim 2016). The lower adsorption yield in basic medium can be due to the competition between OH⁻ ions and anionic RR75 dye toward the fixation sites. The change in the biosorption trend at pH 12 suggests that a chemisorption process is operating at these conditions. Baskaralingam et al. (2006) and Kurecic and Sfiligoj (2012) reported that color removal mechanism at higher pH values can be explained by the formation of covalent bonds between the external surface –OH groups of the adsorbent and the negatively charged dye molecules. By the other hand, increase in the pH value from 2 to 12 was not accompanied with any change in the AO51 removal percentage (over than 90%). In addition to the high electrostatic attraction existing between the positively charged surface of the adsorbent and the anionic dye (Garg et al. 2004), the stability in dye removal capacity by PPCP is also attributed to the dye chemistry as well as the PPCP surface properties and morphology.

Fig. 5 Effect of temperature on RR75 and AO51 biosorption (biosorbent concentration = 20 g L⁻¹ and 10 g L⁻¹ respectively for RR75 and AO51; dye concentration = 100 mg L⁻¹; incubation time = 30 min; pH = 2)

Effect of temperature

Adsorption of RR75 and AO51 on PPCP was investigated at different temperatures from 20 to 60 °C for the initial dye concentration of 100 mg L⁻¹ at constant adsorbent dose and a pH=2. Figure 5 shows that adsorption of both dyes slightly increased with the rise in temperature from 20 to 60 °C. Decolorization yield increased from 92.79 and 88.87% to 95.78 and 93.77% with an increase in temperature from 20 to 50 °C, for RR75 and AO51, respectively. The adsorption capacity increased with increasing the solution temperature due to the increase in the diffusion rate of the adsorbed molecules across the external boundary layer and the internal pores of the biosorbent particles. This result suggests that the adsorption process is endothermic.

Adsorption kinetics

Obtained data showed that Elovich, pseudo-first and pseudo-second order models, but not intra-particle diffusion, greatly

correlate with the experimental findings (Table 2). However, the fitting of pseudo-second order model was found to be the most closer to one ($R^2 \geq 0.999$) compared to other models. These results suggest that the rate-controlling step of AO51 and RR75 biosorption onto PPCP is presumably a chemisorption process involving electrons exchange. Methylene Blue (MB), Eriochrome Black T (EBT) and Alizarin S (AS) biosorption kinetics data on dried prickly pear cactus cladodes were properly fitted with the pseudo-second-order model according to Barka et al. (2013b). Similar phenomena have been observed in the kinetic studies on biosorption of methyl orange, methylene blue and congo red on aminated pumpkin seed powder, sugar beet pulp and cashew nut shell, respectively (Senthil Kumar et al. 2010; Subbaiah and Kim 2016; Vučurović et al. 2012). In contrast, adsorption kinetic study of five acid dyes (CAcid Green 25, and Acid Red 73) onto chitosan, derived from crab-shell chitin, demonstrated that pseudo-first order model well described the acidic dyes adsorption kinetics (Wong et al. 2004). Similar results were obtained also by Ayanda et al. (2012) for the adsorption kinetic of Congo Red onto kola nut pod carbon.

Table 2 Kinetic constants and statistical parameters of RR75 and AO51 biosorption onto dried cactus cladodes

Model	RR75	AO51
Pseudo-first order		
$q_{\max}$	4.8990	9.8760
k_1	0.2250	0.3050
R^2	0.9991	0.9998
R^2_{adj}	0.9989	0.9998
RMSE	0.0529	0.0467
SSE	0.0196	0.0153
Pseudo-second order		
$q_{\max}$	4.9600	9.8920
k_2	0.2660	0.7848
R^2	0.9996	0.9999
R^2_{adj}	0.9995	0.9999
RMSE	0.0350	0.0392
SSE	0.0086	0.0107
Intra-particle diffusion		
k_p	0.3647	0.7155
C	1.7760	3.7470
R^2	0.6082	0.5733
R^2_{adj}	0.5522	0.5123
RMSE	1.0890	2.2960
SSE	8.3000	36.910
Elovich model		
A	12,270	16,740
B	2.9860	1.4330
R^2	0.9903	0.9812
R^2_{adj}	0.9889	0.9785
RMSE	0.1712	0.4818
SSE	0.2051	1.6250

Adsorption isotherms

A comparison of the statistic parameters values of the six isotherms models Langmuir, Freundlich, Dubinin–Raduskevich, Temkin, Redlich–Peterson, and BET models for both dyes suggested that the best fit for the experimental data was provided by BET and Langmuir models for RR75 and AO51 respectively (Table 3; Figs. 6, 7). In fact, the following models presented, in order, excellent fits to RR75's experimental data: BET > Redlich–Peterson > Freundlich > Langmuir, while for AO51's experimental data, the order was as follows: Langmuir > Temkin > BET. The obtained results suggest that adsorption is multilayer in case of RR75 and monolayer for AO51. According to the Langmuir model, the maximum monolayer biosorption capacities of RR75 and AO51 were found to be 198.9 and 45 mg g⁻¹, respectively. Table 4 shows some of previously reported findings on the biosorption capacities of various low-cost biosorbents of Acid Orange (AO) and Reactive Red (RR) dyes families. The experimental data of the present study was found to be comparable to those of many other biosorbents in the literature. Several biosorbent characteristics can influence the sorbent adsorption efficiency such as chemical activation, biosorbent particles size, specific surface area and nature of the functional groups at the biosorbent surface (Gupta and Suhas 2009). Chemically activated *Opuntia ficus indica* fruit waste with NaOH and NaClO showed better adsorption capacity than untreated biomaterial respectively for direct and basic dyes. Barka et al. (2013b) reported that PPCP

Table 3 Adsorption isotherm constants and statistical parameters for biosorption of RR75 and AO51 by dried cactus cladodes powder

Model	RR75	AO51
Langmuir model		
q_m	198.90	45.000
K_L	0.0028	0.0343
R^2	0.9916	0.9646
R^2_{adj}	0.9910	0.9602
RMSE	2.9060	3.1360
SSE	126.60	78.700
Freundlich model		
N	1.4520	2.8950
K_F	1.7950	6.0160
R^2	0.9917	0.8883
R^2_{adj}	0.9912	0.8743
RMSE	2.8780	5.5730
SSE	124.20	248.50
Temkin model		
A	0.1432	0.4420
B	133.80	289.10
R^2	0.7345	0.9586
R^2_{adj}	0.7124	0.9534
RMSE	15.820	3.3930
SSE	3004.0	92.120
Dubinin–Raduskevich model		
q_m	90.890	38.90
B	0.000929	0.0000559
R^2	0.8571	0.9166
R^2_{adj}	0.8476	0.9061
RMSE	11.970	4.8170
SSE	2149.0	185.60
Redlich–Peterson model		
K_R	0.8135	3.4170
α_R	0.0528	0.3692
B	0.6057	0.7203
R^2	0.9928	0.9204
R^2_{adj}	0.9918	0.8976
RMSE	2.7740	5.0300
SSE	107.70	177.10
BET model		
q_{mono}	94.490	33.22
C	1272	1200
A	8.817	71.320
R^2	0.9931	0.9485
R^2_{adj}	0.9921	0.9421
RMSE	2.7270	3.7830
SSE	104.10	114.50

adsorption yield increased from 54.91 to 118.80 mg g⁻¹ for a decrease in particles size from bigger than 500 mm to smaller than 100 mm. By the other hand, adsorption

Fig. 6 Effect of RR75 concentration on its biosorption by PPCP ($R = 20$ g/L, contact time = 30 min, temperature = 30 °C and pH = 2) **Fig. 7** Effect of AO51 concentration on its biosorption by PPCP ($R = 10$ g/L, contact time = 30 min, temperature = 30 °C and pH = 2)

efficiency is closely related to the dyes particular structure (Gupta and Suhas 2009).

Conclusion

Dyes adsorption capacity of prickly pear cactus cladodes powder of *Opuntia ficus indica* was studied using four kinetic models and six isotherm models. The two studied dyes presented different adsorption behaviors. In fact, RR75 was pH dependent, obeying to the pseudo-second order kinetic model and well described by the BET isotherm model. In the other side, AO51 adsorption, better fitted with the second-order kinetic model, was closely

Table 4 Adsorption capacities and other parameters for the removal of acid orange and reactive red dyes families by commercial activated carbons and other alternative adsorbents

Adsorbent	Adsorbate	Adsorption capacity (mg g ⁻¹)	Incubation time	References
Activated Carbon-Sugarcane bagasse	Acid orange 10	15.78	20 h	Tsai et al. (2001)
Chitosan	Acid orange 12	973.3	24 h	Wong et al. (2004)
Banana peel	Acid orange 52	121	24 h	Annadurai et al. (2002)
Orange peel		120.5	24 h	Annadurai et al. (2002)
Chitosan bead (chemically crosslinked)	Acid orange 12, acid orange 7	1954, 1940	5 days	Chiou et al. (2004)
Spent brewery grains	Acid orange 7	29	36 min	Silva et al. (2004)
Activated carbon prepared from bentonite	Acid orange 7	238	40 min	Silva et al. (2004)
Modified wheat husk	Acid orange 10	31.25	30 min	Banerjee et al. (2016)
PPCP	Acid orange 51	45	30 min	This study
Metal hydroxide sludge	Reactive red 2	62.50	–	Netpradit et al. (2003)
Chitosan flake (shrimp)	Reactive red 222	494	3 days	Wu et al. (2000)
Modified sepiolite	Reactive red 239	108.8	–	Ozdemir et al. (2004)
Modified cellulose from flax shive	Reactive red 228	190	3 h	Wang and Li (2013)
Biomass <i>Rhizopus arrhizus</i>	Reactive red 4	150	–	Wu et al. (2000)
PPCP	Reactive Red 75	189.9	30 min	This study

adjusted to the Langmuir isotherm model. For both dyes, PPCP of *Opuntia ficus indica* was shown to be low-cost, ecofriendly and efficient biosorbent for dye removal from aqueous solutions. In-depth study incorporating the effect of particles size and optimization of all adsorption parameters using experimental design tools will be needed for the development of an ecofriendly industrial-scale treatment.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest in the publication OR.

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