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Research Article

Sustainable Dye Removal from Aqueous Media Using *Paronychia carica* as a Natural Biosorbent

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Abstract: This study explores the use of sustainable natural resources in wastewater treatment, focusing on *Paronychia carica*, a member of the Magnoliopsida class, as a biosorbent for removing Procion Red dye (PR) from aqueous solutions. The effects of pH, initial dye concentration, adsorbent dosage and contact time on the adsorption performance were systematically investigated. Maximum dye uptake (83%) was achieved after 4 hours with an initial dye concentration of 30 mg L^{-1} and 0.5 g ofadsorbent at a mildly acidic pH of 4.0. Kinetic analysis revealed that the adsorption process followed the pseudo-second-order (PSO) model, with the calculated equilibrium capacity closely matching the experimental value, highlighting the dominant role of available adsorption sites. Equilibrum data were best described by the Freundlich, Dubinin-Radushkevich and Temkin isotherm models, confirming adsorption on a heterogeneous surface. The mean free adsorption energy from the D–R model (E = 8.53 kJ mol^{-1}) indicated that the physisorption is the primary mechanism. These findings demonstrate that *P. carica* can efficiently and rapidly remove PR dye under mild conditions. Overall, the study highlights the potential of *P. carica* as a low-cost, sustainable biosorbent for textile wastewater remediation, promoting eco-friendly treatment and supporting global efforts to reduce industrial pollution.

Keywords: *Sustainability, Biosorption, Isotherm, Dye removal, Paronychia carica*

I. INTRODUCTION

The pigments and dyes are widely used in the textile and leather industries, to provide the best color matches and finishes. The discharge of textile dye effluents into natural water bodies has become a significant environmental concern due to their potential toxicity, persistence, and aesthetic impact (Cardoso et al., 2012; Katheresan et al., 2018; Yagub et al., 2014). Synthetic dyes, such as azo dyes, are particularly challenging to remove because of their complex molecular structures and resistance to conventional wastewater treatment methods (Almeida & Corso, 2014). As a result, there is an increasing demand for effective and sustainable approaches to dye removal that minimize environmental impact and operational costs.

Several techniques, including flocculation/coagulation, adsorption, and chemical oxidation, are employed for treating dye-laden wastewaters (Kasperchik et al., 2012; Sudamalla et al., 2012; Rodrigues et al., 2009). Very high color removal can be obtained efficiently by methods such as ozonation, chlorination, ultrafiltration, and electrochemical oxidation, but the main disadvantage of these methods is the cost (Gupta & Suhas, 2009).

Biosorption, a process that utilizes natural materials to adsorb contaminants, has gained considerable attention as an eco-friendly and cost-effective alternative for dye removal (Gupta & Suhas, 2009; Torres, 2020). Among various natural adsorbents, plant-based materials have shown promise due to their abundant availability and presence of functional groups capable of binding dye molecules (Sharma et al., 2011; Velmurugan et al., 2011; Noreen et al., 2013; Deniz, 2014; Nawaz et al., 2013). In this context, *Paronychia carica* (*P. carica*), a plant traditionally used in herbal medicine, emerges as a potential candidate for textile dye biosorption.

There are about 110 species of the genus *Paronychia* Mill. in the world, and Türkiye is very rich in this plant. *Paronychia* is a genus in the Illecebraceae family of the Caryophyllales ordo and is represented by 41 taxa, 28 of which are endemic to this country. A total of 10 species, 4 of which are endemic, have been identified in the Aegean region (Budak et al., 2017; Davis et al., 1988; Chaudhri, 1967).

The potential of *Paronychia carica* as an efficient biosorbent can be attributed to its lignocellulosic content and the presence of functional groups, which serve as active sites for dye adsorption (Deniz, 2014). Additionally, the saponin content in *P. carica* (Avunduk et al., 2007) may enhance its biosorption capabilities by facilitating the incorporation of dye molecules into micelles (Samal et al., 2017). The modification of biosorbent surfaces through treatments, such as acid

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washing, further improves their adsorption capacity by increasing surface area and binding site availability (Bharathi & Ramesh, 2013).

This paper provides new insights into the adsorption mechanisms of Procion Red dye using *Paronychia carica* as a biosorbent. By evaluating the effects of parameters such as pH, contact time, and adsorbent dosage, this study aims to elucidate the potential of *P. carica* in textile wastewater treatment. These findings may facilitate the development of efficient, sustainable, and cost-effective strategies for dye removal, thereby promoting cleaner water resources and advancing environmental sustainability.

II. MATERIAL AND METHOD

A. *Materials*

In this study, P. carica was employed as a natural biosorbent for the removal of Procion Red (PR) dye, commercially known as Reactive Red 141 (DyStar, Turkey), from aqueous solutions. This particular dye was selected due to its broad use in textile applications and was employed as a model pollutant to evaluate the adsorption performance of the selected biosorbent. The chemical composition of PR dye is presented in Figure 1. The chemicals used in the experimental studies, such as HCl, NaOH, and H_3PO_4, were purchased from Merck (Germany) and used without further purification.

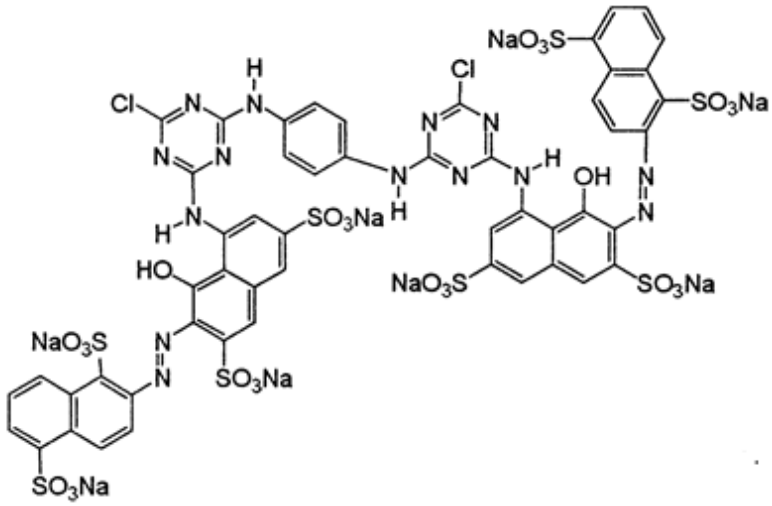


Figure 1. Chemical structure of Procion Red dye

B. *Collection and Identification of Paronychia carica*

Paronychia carica Chaudhri plants were collected from the vicinity of Vakıfköy sand quarries in the Tavas district of Denizli province (Figure 2). The collected plant material was brought to the laboratory for use as a biosorbent. To eliminate surface impurities and adhering soil particles, the plant samples were thoroughly washed with distilled water. The cleaned samples were then dried in an oven at 100±5°C until a constant weight was achieved. After drying, the material was lightly ground using a mortar and subsequently sieved to obtain particles with a size smaller than 125 µm. This preparation procedure was applied to obtain a homogeneous biosorbent with a controlled particle size suitable for adsorption experiments.

The surface morphology of the prepared biosorbent was examined by scanning electron microscopy (SEM) using a JEOL JSM-6490 instrument (Japan). Prior to SEM analysis, the samples were sputter-coated with gold, and the images were recorded at an accelerating voltage of 5 kV.



Figure 2. *Paronychia carica*

C. Batch Adsorption Studies

The stock solutions of the PR dye were prepared, and sequential dilutions of these stock solutions were carried out for the experiments. The concentration of the dye was monitored using spectrophotometry at a wavelength of 540 nm (Optizen Pop, South Korea). Experiments were conducted in 50 mL Erlenmeyer flasks using a thermostatically controlled shaking water bath (Daihan, South Korea), with a solution volume of 30 mL and a stirring speed of 200 rpm. The pH of the solutions was adjusted by adding dilute HCl or NaOH solution.

Batch adsorption experiments were conducted by varying key experimental parameters, including the mass of the adsorbent, initial dye concentration, contact time, and solution pH, consistent with similar studies evaluating dye removal in aqueous systems (Yadav et al., 2024).

The PR dye solutions were calibrated to measure the various optical densities at various concentrations of PR dye (2.5, 5, 10, 20, 30, and 40 mg L^{-1}) in the distilled water. R^2 factor was calculated from the graph (Figure 3), as an absorbance vs concentration.

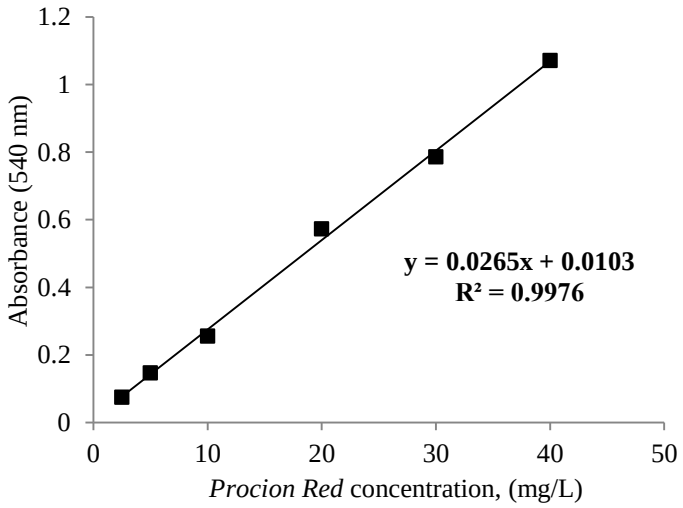


Figure 3. Calibration curve of PR solutions at 540 nm

The effect of pH, adsorbent mass, and initial dye concentration was investigated as follows: The point of zero charge (pH_{pzc}) of the biomass was determined using the pH drift method. Briefly, 0.1 g of adsorbent was added to 50 mL of 0.01 M NaCl solution with initial pH values adjusted between 2 and 10. The suspensions were shaken at 200 rpm at 25°C for 24 h. The final pH values were recorded, and pH_{pzc} was determined from the point where ΔpH ($pH_{final} - pH_{initial}$) equals zero. The impact of pH was assessed at values of 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, and 9.0, using an initial dye concentration of 30 mg L^{-1}, an adsorbent mass of 0.5 g, at 25°C, and an agitation period of 4 hours. Subsequently, the influence of varying adsorbent masses (0.5, 1.0, and 2.0 g) was evaluated using 30 mL of dye solution with an initial concentration of 30 mg L^{-1}. Finally, the effect of initial dye concentration was examined by varying the PR dye concentration from 10 to 80 mg L^{-1} at 25°C for 24 hours while maintaining a constant adsorbent mass of 0.5 g.

Acid treatment was applied to the biosorbent to modify its surface characteristics by enhancing the availability of active functional groups and improving the interaction between *P. carica* and PR dye molecules. Following treatment with 10 M H_3PO_4, kinetic curves were developed using contact times of 15, 30, 45, 60, 120, and 240 minutes, with an initial dye concentration of 30 mg L^{-1}, an adsorbent mass of 0.5 g, at 25°C, and a pH range of 2.0 to 9.0. Subsequently, equilibrium isotherms were generated at 25°C using dye concentrations from 10 to 80 mg L^{-1}, with a biosorbent mass of 0.5 g and a pH of 4.

D. Data Analysis

The dye removal percentage (R, %) and the quantity of PR adsorbed per gram of biosorbent at equilibrium (q_e, mg g^{-1}) were calculated according to equations (1) and (2), respectively.

$$R\ (\%) = \frac{(C_0 - C_e)}{C_0} \times 100 \quad (1)$$

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (2)$$

where C_0 represents the initial concentration of PR (mg L^{-1}), C_e denotes the equilibrium concentration of PR (mg L^{-1}),

m is the mass of biosorbent (g), and V is the volume (L).

Adsorption isotherms were analysed with four widely applied empirical models: Langmuir, Freundlich, Dubinin-Radushkevich (D–R), and Temkin isotherms.

The Langmuir model provides a theoretical explanation of adsorption as a homogeneous monolayer on a defined number of active sites on the adsorbent surface, suggesting that saturation is reached at specific concentrations of pollutants (Langmuir, 1918). The Langmuir model can be represented by the formula below:

$$\frac{C_e}{q_e} = \frac{1}{Q_{max} b_L} + \frac{C_e}{Q_{max}} \quad (3)$$

where C_e represents the concentration of dye (mg L^{-1}) remaining in the solution in the adsorption medium in equilibrium; q_e shows the quantity of the adsorbed dye (mg g^{-1}), Q_{max} (mg g^{-1}) and b_L (L mg^{-1}) characterize the adsorption capacity and energy-related Langmuir constants in equilibrium. Another way to demonstrate the effectiveness of the adsorption process is the R_L dimensionless constant. This constant can be found using the following formula:

$$R_L = \frac{1}{1 + b_L C_0} \quad (4)$$

Here, b_L indicates the energy-related Langmuir constant (L mg^{-1}) and C_0 is the initial dye concentration (mg L^{-1}).

The Freundlich isotherm, representing adsorption on heterogeneous surfaces, points to an exceptional case toward heterogeneous surface energies (Freundlich, 1906). The Freundlich model is typically seen as more practical, illustrating how adsorption occurs on heterogeneous surfaces and increases with the amount of adsorbent. It is generally defined as:

$$log\ q_e = log\ K_F + \frac{1}{n_F} log\ C_e \quad (5)$$

where K_F (mg g^{-1}) represents the Freundlich constant for the adsorption capacity, n_F is a dimensionless constant related to adsorption intensity, and $1/n_F$ is the heterogeneity factor with a value between 0 and 1. Smaller values of $1/n_F$ indicate more heterogeneous surfaces (Nizam et al., 2024).

Another widely utilized isotherm is the D–R model, which is used to assess the apparent free energy of adsorption (Dubinin et al., 1947). The linearized version of the D–R isotherm equation is shown below:

$$ln\ C_{ads} = lnX_m - \beta\varepsilon^2 \quad (6)$$

where C_{ads} (mol g^{-1}) represents the amount of solute adsorbed per unit mass of the solid, X_m (mol g^{-1}) denotes the adsorption capacity, β (mol² kJ^{-2}) is a constant related to adsorption energy, and ε is the Polanyi potential. The Polanyi potential can be calculated using the formula below:

$$\varepsilon = RTln(1 + \frac{1}{C_e}) \quad (7)$$

where R is the gas constant in J mol^{-1} K^{-1}, and T is the temperature in Kelvin. When lnC_{ads} is plotted against ε^2, β and X_m can be obtained from the slope and intercept. The energy of adsorption (E) is calculated using the formula with the constant β.

$$E = 1/\sqrt{2\beta} \quad (8)$$

The Temkin model accounts for the impact of intermolecular interactions among adsorbed molecules on the adsorption process. It assumes that the heat of adsorption decreases linearly as the coverage of the adsorbent surface increases, due to these interactions. The Temkin isotherm derivation treats adsorption as a multilayer process and assumes a uniform distribution of binding energies, up to a specified maximum binding energy (Nizam et al., 2024; Sharifi et al., 2021). The Temkin model can be expressed in linearized form as follows:

$$q_e = B_T lnA_T + B_T lnC_e \quad (9)$$

In this equation, A_T (L g^{-1}) and B_T (J mol^{-1}) represent the Temkin constants related to the equilibrium binding constant and the heat of adsorption, respectively. The Temkin constant B_T is defined by the expression:

$$B_T = {RT}/{b_T} \quad (10)$$

where R denotes the universal gas constant, T the absolute temperature in Kelvin, and b_T is the Temkin constant related to the heat of sorption (J mol^{-1}).

The adsorption kinetics of PR dye onto *P. carica* were evaluated using the Pseudo-First Order (PFO) and Pseudo-Second Order (PSO) kinetic models. The linear form of the PFO model is expressed as:

$$\ln(q_e - q_t) = lnq_e - k_1 t \quad (11)$$

where q_t (mg g^{-1}) is the amount of dye adsorbed at time t, q_e (mg g^{-1}) is the equilibrium adsorption capacity, and k_1 (min^{-1}) is the PFO rate constant. The PFO model is generally applicable when the rate of adsorption is proportional to the number of unoccupied sites, which is often observed in physisorption-dominated processes.

The PSO model assumes chemisorption as the rate-limiting step and is represented in its linear form as:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \quad (12)$$

where k^2 ($g.mg^{-1}min^{-1}$) is the PSO rate constant.

III. RESULTS AND DISCUSSIONS

A. *SEM Observation of P. carica*

In this study, SEM was used to determine the physical characteristics of the adsorbent. SEM micrographs of *P. carica* are presented in Figure 4. The images clearly showed that the biosorbent has a rough and irregular surface morphology with the presence of cavities on its outer surface and numerous fibers. Such morphological features are typically associated with an increased surface area and more active sites, which enhance the material's adsorption performance.

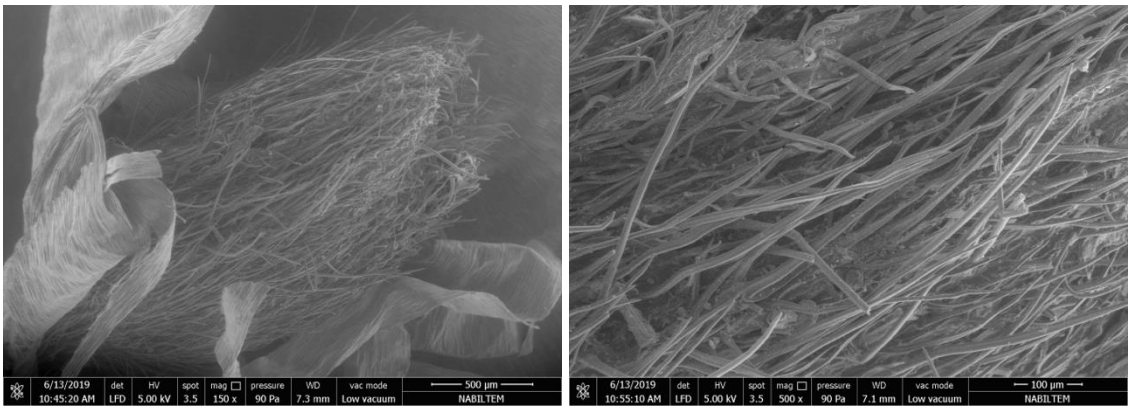


Figure 4. SEM images of *P. carica*

The findings were consistent with the previous observations on *P. carica*. The flowers of the plant are described as oblong or narrowly ellipsoid, densely, and appressed hairy surfaces covered with soft shining hairs (Chaudhri, 1966).

B. *Effect of pH on the Adsorption Process*

The pH of the adsorption medium can considerably affect the electrostatic charges on ionized dye molecules, making it one of the most critical process parameters (Gönen & Önalan, 2016). The adsorption rate can vary with the pH of the aqueous solution; therefore, experiments were carried out across a pH range of 2.0 to 9.0 for an initial PR dye concentration of 30 mg L^{-1}, an adsorbent amount of 0.5 g in 30 mL solution, a temperature of 25°C, and a contact time of 4 hours. Higher pH values were not explored to prevent precipitation.

The point of zero charge (pH_{pzc}) of the biomass was determined as 7.06 (Figure 5), indicating that the adsorbent surface is positively charged at pH values below 7.06 and negatively charged above this value.

The effect of pH on the adsorption of PR dye is illustrated in Figure 6. Figure 6 clearly demonstrates that PR dye removal improves with an increase in pH from 2.0 to 4.0 and then remains nearly constant between pH 4.0 and 6.0 and gradually decreases at higher pH values. For instance, the maximum PR dye removal efficiencies at pH 3.0 and pH 4.0 were 80.3% and 83.2%, respectively, whereas the removal efficiency decreased to 66.3% at pH 9.0.

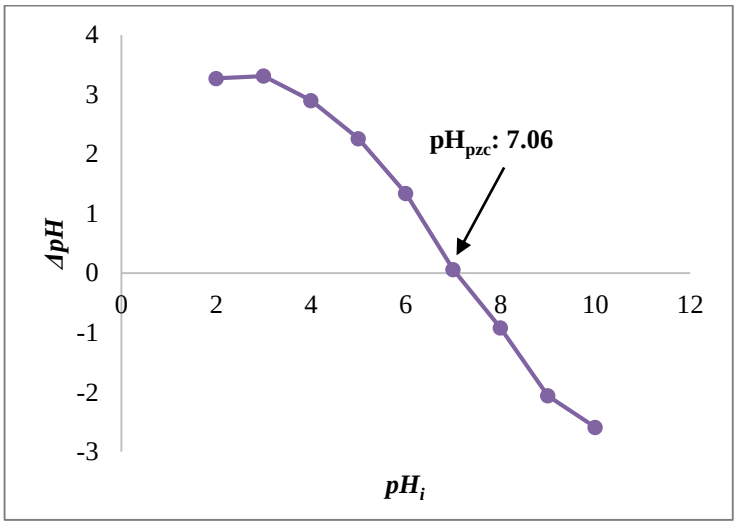


Figure 5. Point Zero Charge (pH_{pzc}) for adsorbent

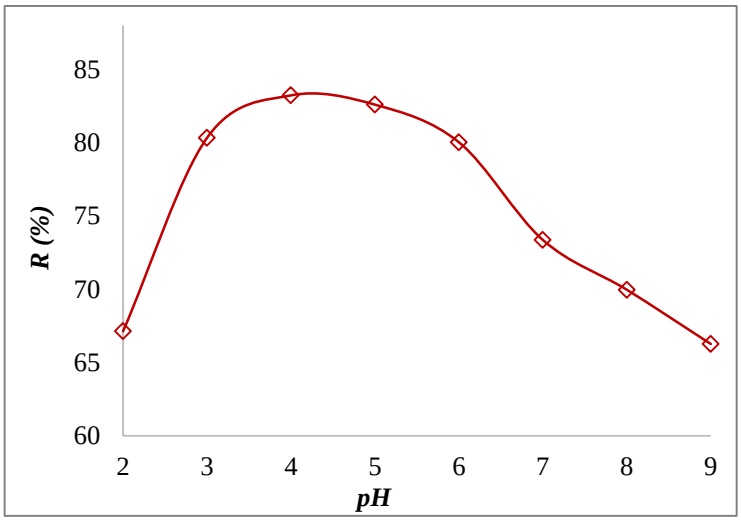


Figure 6. Effect of pH on the adsorption of of the PR dye by *P. carica*

Notably, the pH region corresponding to maximum adsorption (pH 4.0) lies below the pH_{pzc} (7.06), where the surface is predominantly protonated and positively charged. Under these conditions, strong electrostatic attraction occurs between the positively charged functional F groups on the biomass surface and the negatively charged sulfonate groups of PR dye molecules. This confirms that electrostatic interactions are a dominant driving force.

At pH values above 7.06, adsorption decreases due to deprotonation of surface functional groups and the development of a negatively charged surface, resulting in electrostatic repulsion with the anionic dye. At strongly acidic conditions (pH 2.0), although the surface is highly protonated, adsorption is slightly lower than at pH 4.0 due to competition between excess H^+ ions and dye molecules for adsorption sites (Gönen & Önalan, 2016; Hameed, 2009).

Previous studies have shown that anionic dye adsorption is generally favored under acidic conditions due to increased protonation of adsorbent surface functional groups, which enhances electrostatic attraction between the positively charged adsorbent surface and negatively charged dye molecules, whereas higher pH leads to deprotonation and reduced electrostatic affinity for anionic dyes (Wong et al., 2020).

As PR adsorption remained nearly constant from pH 4.0 to 6.0, pH 4.0 was selected as the most effective condition for subsequent adsorption experiments. This pH value is also consistent with the typical pH range of textile wastewater, supporting the potential applicability of the proposed adsorbent for practical and industrial dye removal processes.

C. Effect of Adsorbent Dosage

Adsorbent dosage is a critical operational parameter in adsorption studies, as increasing the sorbent mass at a fixed dye concentration generally enhances the number of available active sites and total surface area, while excessive dosage

may lead to particle aggregation and inefficient site utilization (Yadav et al., 2024). The removal of PR dye by *P. carica* was investigated at various adsorbent amounts (0.5, 1.0, and 2.0 g) in 30 mL of dye solution with a concentration of 30 mg L^{-1} at 25°C and pH 4.0. Figure 7 demonstrates that dye adsorption increases with increasing adsorbent amounts. When the sorbent mass is increased from 0.5 to 2.0 g, the PR removal efficiency rises from 81.7% to 84.7% after 24 hours of contact, whereas further increase to 2.0 g results in a slight decrease to 80.7 %. This improvement up to 1g can be attributed to the larger available surface area and additional binding sites for dye molecules (Garg et al., 2004), whereas the slight decline at 2 g may be due to the limited availability of dye molecules relative to the adsorbent surface or partial aggregation of sorbent particles, which reduces the effective surface area (Yadav et al., 2024; Gönen & Önalan, 2016).

These results suggest that an optimal sorbent mass exists that can achieve high removal efficiency without unnecessary material usage, supporting practical and economic application of *P. carica* for dye removal in aqueous systems.

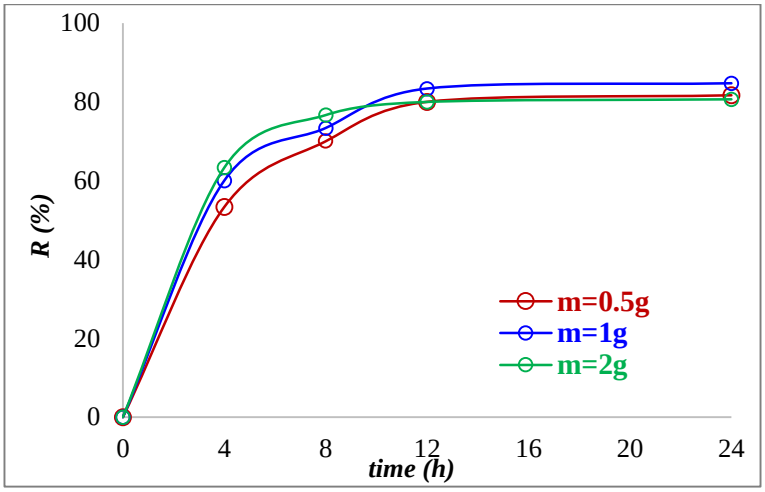


Figure 7. Effect of adsorbent dosage on the adsorption of the PR dye by *P. carica*

D. Effect of Dye Concentration

The adsorption capacity of *P. carica* for different initial dye concentrations of 10, 20, 30, 40, and 80 mg L^{-1} under the same experimental conditions (m = 0.5 g, V = 30 mL, pH 4, T= 25°C). As shown in Figure 8, dye adsorption is rapid during the first 4 h and then gradually slows down until equilibrium is reached. The amount of dye adsorbed per gram of *P. carica* (qe) increases with the initial dye concentration, reaching 0.452 mg g^{-1} at 10 mg L^{-1}, 1.632 mg g^{-1} at 30 mg L^{-1}, and 2.94 mg g^{-1} at 80 mg L^{-1} after 4 h. In contrast, the removal efficiency (R) decreases at higher concentrations due to saturation of available binding sites (Dabbagh et al., 2016), with R values of 75.4%, 90.7%, and 61.3% for 10, 30, and 80 mg L^{-1}, respectively. A slight decline in adsorption is also observed at longer contact times, likely due to the redistribution of dye molecules and surface site saturation. These results indicate that *P. carica* exhibits high adsorption capacity at moderate dye concentrations, while very high concentrations reduce removal efficiency due to limited availability of binding sites. In the context of real textile wastewater, dye concentrations in industrial effluents have been reported over a wide range, frequently spanning from 10 to 200 mg L^{-1} (Hussein & Scholz, 2017), which covers the concentration range investigated in the present study.

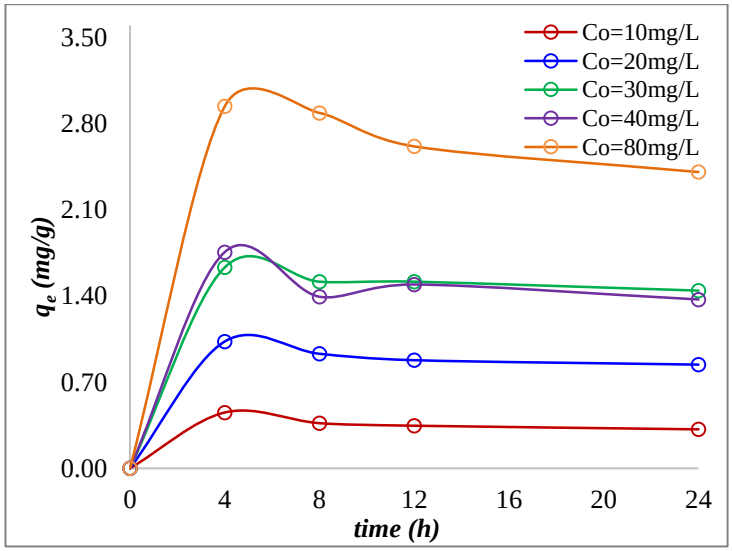


Figure 8. Effect of dye concentration on adsorption of the PR dye by *P. carica*

E. Effect of Phosphoric Acid Treatment

Phosphoric acid activation is commonly applied to lignocellulosic materials because it enhances surface area and porosity and promotes the development and exposure of surface functional groups that act as active sites for adsorption, thereby improving adsorption performance. Chemical activation with phosphoric acid significantly improves surface reactivity and functionalization of the adsorbent, leading to enhanced dye uptake (Flores-Céspedes et al., 2025). To investigate this effect on *P. carica*, the material was treated with 10 M H_3PO_4.

The acid treatment significantly enhanced the adsorption capacity for PR dye. As seen in Figure 9, the highest adsorption capacity was observed at mildly acidic conditions (pH 4–5), reaching qe values of 1.62 and 1.44 mg g^{-1} with removal efficiencies of 90% and 80%, respectively. The time-dependent data indicate that adsorption increased rapidly in the first 60 minutes and then gradually approached equilibrium around 120 minutes, suggesting the gradual occupation of active sites generated by the acid treatment. At more acidic (pH 2–3) or basic (pH 8–9) conditions, the adsorption was lower, demonstrating that the acid treatment created active sites that are more effective under mildly acidic conditions. This behavior can be attributed to modifications in the surface chemistry induced by phosphoric acid. In plant-based biosorbents, phenolic, carboxyl, and hydroxyl groups are known to play a key role as binding sites for dye molecules, facilitating electrostatic interactions and hydrogen bonding with the adsorbed species (Georgin et al., 2017).

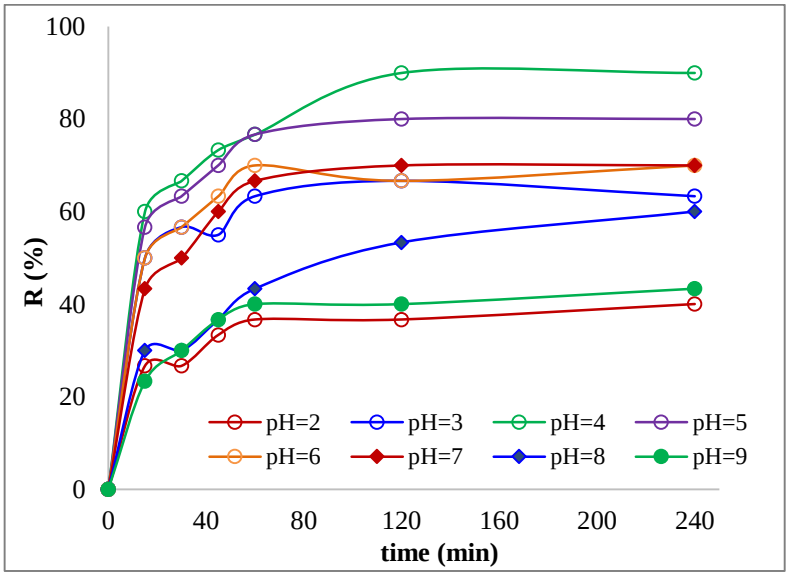


Figure 9. The adsorption of PR dye onto *P. carica* treated with 10 M H3PO4

F. Equilibrium Isotherms

In this study, the experimental equilibrium data for PR dye adsorbed on *P. carica* were evaluated using the Langmuir, Freundlich, Dubinin-Radushkevich, and Temkin isotherm models, as shown in Figure 10 (Linearized isotherms). The experimental results obtained from the adsorption equilibrium data showed good compatibility with the Freundlich, D–R, and Temkin isotherms. To further confirm the validity of the isotherm analysis, the nonlinear forms of the Langmuir, Freundlich, and Temkin models were also plotted, as presented in Figure 11. The computed constants of the isotherms, obtained from the linearized models, are given in Table 1.

The Freundlich model assumes that biosorption occurs on a heterogeneous surface with energy sites of an exponential nature (Freundlich, 1906). According to the correlation coefficients, the Freundlich equation provides a good description of the adsorption process (R^2=0.92). The value of 1/n < 1 suggests that sorption capacity is slightly reduced at low equilibrium concentrations, predicting multilayer adsorption on a heterogeneous surface. This indicates a suitable and beneficial biosorption process. The heterogeneous structure of the biosorbent was also confirmed by SEM observations (Figure 3). The rough surface morphology of the biosorbent, with the presence of numerous fibres, enhances the availability of active sites, facilitating the trapping and biosorption of dye molecules. The nonlinear Freundlich curve shown in Figure 11 further supports this behavior through its good agreement with the experimental adsorption data over the studied concentration range.

The obtained results also show good agreement with the D–R isotherm model (R^2=0.94). The adsorption capacity (X_m) calculated from the D–R model is 2.43 mg g^{-1} for PR dye. The mean free adsorption energy (E) derived from the D–R isotherm is used to evaluate the nature of the adsorption mechanism. When the E value lies between 1.00 and 16.00 kJ mol^{-1}, the adsorption process is generally attributed to physical interactions, whereas values above 16 kJ mol^{-1} indicate chemisorption (Saeed, 2003). Since the adsorption energy (E = 8.53 kJ mol^{-1}) falls within this range, the adsorption of PR dye onto *P. carica* is predominantly governed by physisorption. This interpretation is in line with the nonlinear isotherm trends observed in Figure 11.

According to the Temkin isotherm model, the relatively low b_T value (14.53 kJ mol^{-1}) indicates weak adsorbate–adsorbent interactions, suggesting that the heat of adsorption decreases linearly with surface coverage (Aytas et al., 2011). This behavior is consistent with adsorption occurring on a heterogeneous surface with moderate interaction energies. Considering that the initial dye concentration (30 mg L^{-1}) is relatively low for textile dye wastewater, physisorption mechanisms are expected to play a significant role in the overall adsorption process (Ritter et al., 2024). The nonlinear Temkin plot in Figure 11 exhibits a close correspondence with the experimental data, further confirming the applicability of this model.

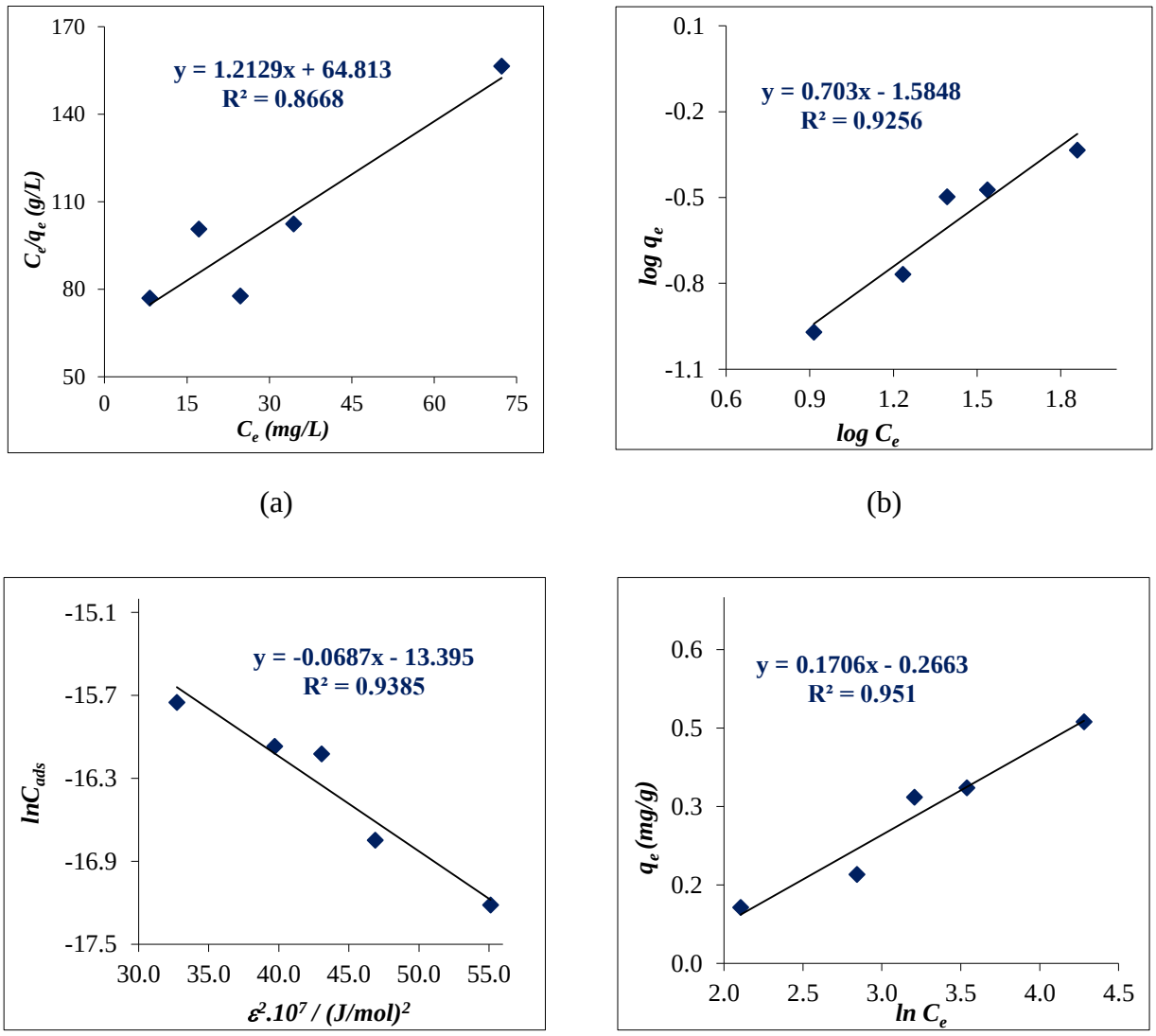


Figure 10. Linearized adsorption Isotherms for PR dye adsorption onto *P. carica*: (a) Langmuir, (b) Freundlich, (c) Dubinin-Radushkevich, (d) Temkin models

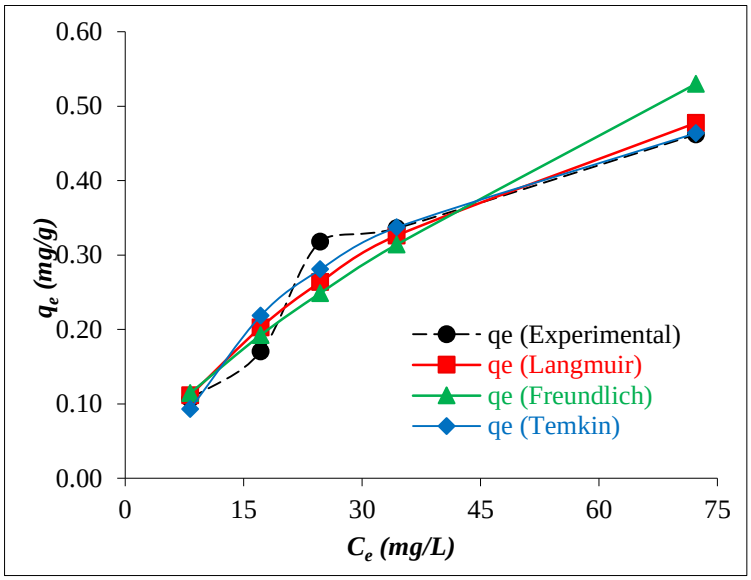


Figure 11. Nonlinear adsorption isotherms for PR dye adsorption onto *P. carica* based on the Langmuir, Freundlich, and Temkin models, showing the comparison between experimental adsorption capacities

Table 1. Parameters obtained from linear Langmuir, Freundlich, Dubinin–Radushkevich, and Temkin isotherm models for PR dye adsorption onto *P. carica*.

Isotherm models	**Parameters**	
Langmuir	Q_{max} (mg g^{-1})	0.825
	b_L (L mg^{-1})	0.019
	R^2	0.87
Freundlich	K_F (mg g^{-1})	0.026
	n_F	1.42
	R^2	0.92
D–R	X_m (mg g^{-1})	2.43
	E (kJ mol^{-1})	8.53
	R^2	0.94
Temkin	A_T (L g^{-1})	0.21
	b_T (kJ mol^{-1})	14.53
	R^2	0.95

G. Kinetic Study

In order to investigate the adsorption mechanism and rate-controlling steps of PR dye onto *P. carica*, the experimental kinetic data were analyzed using the PFO and PSO kinetic models using their linearized forms. Time-dependent adsorption data were fitted to both models to determine the kinetic parameters and to gain insights into the mechanism of adsorption. The adsorption process exhibited a rapid uptake at the initial contact time, followed by a slight decrease in adsorption capacity at longer durations, indicating the establishment of adsorption–desorption equilibrium.

The PSO model showed an excellent agreement with the experimental data, as evidenced by a high correlation coefficient ($R^2 \approx 1$). The equilibrium adsorption capacity (q_e) calculated from the PSO model (1.41 mg g^{-1}) was in close agreement with the experimentally determined value (1.44 mg g^{-1}), confirming the suitability of the PSO model to describe the kinetic behavior of PR dye adsorption onto *P. carica*. However, the PSO rate constant (k_2) was not considered in detail due to very rapid initial adsorption, which limits its reliable determination from linear regression. Similar observations have been reported in adsorption systems exhibiting rapid surface saturation, where the initial fast uptake is due to abundant active sites and the adsorption slows as these sites become occupied (Muliwa et al., 2023).

The PFO model did not adequately represent the experimental data, as it overestimated adsorption at short contact times, resulting in non-physical values. In contrast, the PSO model closely matched the observed kinetics, suggesting that

the adsorption of PR dye onto *P. carica* is mainly governed by the availability of adsorption sites rather than the rate constant. Although the PSO model provided a superior fit, this does not necessarily indicate a chemisorption-dominated mechanism; rather, surface interactions and site availability appear to control the overall adsorption process.

IV. CONCLUSION

The potential of *Paronychia carica* to be used as a biosorbent for removing Procion Red dye from aqueous solutions has been investigated. Plants are known for their lignocellulosic composition, which includes carboxylic, phenolic, and other groups that can create active sites beneficial for dye biosorption. Additionally, the saponin content in *P. carica* may further contribute to dye removal, as dye molecules can be incorporated into saponin micelles, with adsorption occurring on the micelle aggregates.

The highest adsorption rate of PR dye by the biosorbent (0.5 g) was approximately 83%, achieved at pH 4.0 after approximately 4 hours with an initial dye concentration of 30 mg L^{-1}. This concentration range is relevant for textile wastewater with low to moderate dye loads, suggesting that *P. carica* could be effectively applied in pre-treatment stages of dye effluent treatment. Moreover, treatment with 10 M H_3PO_4 slightly increased the adsorption rate, implying that a simple chemical activation step may enhance biosorption capacity without introducing high cost or environmental burden, and could be explored further in future studies.

The equilibrium data for the biosorbent were consistent with the Freundlich, D–R, and Temkin isotherms, indicating that adsorption occurs predominantly through physical interactions on a heterogeneous surface, with multilayer adsorption behavior. SEM images further supported the presence of a porous, irregular structure capable of accommodating dye molecules, consistent with the non-uniform binding behavior suggested by isotherm modelling.

Kinetic analysis revealed that the adsorption process was better described by the pseudo-second-order (PSO) model, indicating that the adsorption rate is governed by surface interactions and the availability of active sites rather than diffusion limitations. Importantly, to our knowledge, this is the first report on the use of *P. carica* for dye adsorption. The natural abundance and local availability of *P. carica*, combined with its low cost and biodegradability, make it a promising candidate for sustainable wastewater treatment applications. Its satisfactory performance under mild experimental conditions highlights its potential for low-cost treatment systems, particularly in regions where advanced technologies may not be feasible.

For future research, several avenues could strengthen the practical applicability of *P. carica* as a biosorbent. Comparative studies with established adsorbents under identical conditions, including statistical evaluation and replicate experiments, would enhance the reliability of adsorption parameters and provide a deeper understanding of adsorption behavior across varying environmental conditions. Exploring the thermodynamic parameters of the adsorption process could yield insights into the spontaneity and heat effects, while additional chemical activation methods could further improve adsorption capacity. Moreover, investigating reusability, regeneration potential, and performance in more complex effluents containing multiple pollutants would broaden the application scope, and dynamic studies, such as column experiments, could assess scalability for industrial use. Such future directions would not only reinforce the findings of this study but also contribute to the development of green, accessible, and economically viable technologies for dye removal.

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