

Article

Phosphate Removal from Water by Using Biomass Obtained from *Arthrospira platensis*

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Abstract

Eutrophication is a significant issue in aquatic systems that receive wastewater from anthropogenic sources. The reduction of phosphate concentration in wastewater and water bodies is essential to reduce the risk of eutrophication. In this study, biomass obtained from *Arthrospira platensis* was used to reduce the phosphorus concentration in water. The biomass samples were characterized by spectroscopic and morphological techniques, such as vibrational spectroscopy (FTIR and Raman) and microscopy assay (SEM). Adsorption studies were conducted to evaluate the removal efficacy of the biomass. Phosphate removal capacity was strongly influenced by pH, with the highest effectiveness observed under acidic conditions (88% removal at pH 4.4) and rapid initial adsorption reaching equilibrium. Kinetic modelling showed a maximum removal efficacy ($q_e = 2.4 \text{ mg g}^{-1}$ and $k_2 = 0.305 \text{ min}^{-1}$). Isothermal adsorption analysis showed that the Langmuir model described properly experimental results showing physical chemical parameters ($q_{max} = 2.8 \text{ mg g}^{-1}$ and $K_L = 1.41 \text{ L mg}^{-1}$).

Keywords: eutrophication; phosphate removal; adsorption; biomass



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1. Introduction

Anthropogenic alterations to the biogeochemical cycle of phosphorus have a significant impact on water quality in aquatic environments. Excessive phosphate concentrations lead to uncontrolled algal blooms, a primary cause of nutrient pollution and environmental degradation, known as eutrophication [1,2]. Algal blooms limit light penetration, negatively affecting phototrophic and photoheterotrophic organisms. In addition, they contribute to oxygen depletion and pose serious threats to aquatic ecosystems [3,4].

Recently, different technologies and bioremediation strategies have been developed to mitigate phosphate pollution, aiming to reduce phosphate levels in water and minimizing the associated environmental impacts [5]. Among these, chemical treatments are commonly used due to their high efficiency, especially when combined with biological agents. Among all reagents employed in chemical methods, aluminum sulfate is the most commonly used metal salt. This salt reacts with phosphate in solution to form solid precipitates, which are then removed from water through a traditional physical separation method (e.g., filtration,

clarification) [6,7]. Furthermore, modifications of coagulants offer a promising alternative for improving phosphate removal from water. Titanium-containing reagents are also used for phosphate removal [8]. However, chemical methods may produce harmful by-products through reactions with other compounds present in the water matrix, which can further damage the ecosystem [9]. The need of acid or alkali additives during chemical process can also boost sludge production [10,11].

In contrast, biological methods offer a more environmentally friendly alternative, supported by decades of biotechnological advancements. Bioremediation techniques are favored for their minimal ecological impact, though they can face challenges such as nutrient costs, bioreactor design, culture stabilization, and microorganism selection [12]. This technique requires less chemical loads but requires specific microbial and environmental conditions [13].

Biosorption-based techniques have demonstrated effective phosphate removal from water, employing different materials (nanoparticles, nanocomposites, and activated carbon) [14]. This methodology is not expensive compared with traditional methods, and its implementation is easier, offering the possibility of recovering the sorbent material and low quantities of by-products after its implementation [15]. Typical adsorbents employed in phosphorus removal include the following: (i) carbonaceous materials [16], (ii) zeolites [17], (iii) clays [18], (iv) layered double hydroxides [19]. In the last decade, microorganism-based sorbents have represented a promising alternative to complement conventional materials used in adsorption processes [20]. Biomass-based adsorption is gaining attention due to its costs of implementation, low environmental risk, and the availability of biosorbent materials in nature [21]. Different natural sources have been employed to obtain sorbent materials to remove phosphate from water (e.g., wheat straw [22], sawdust [23], eggshell wastes [24], corn straw [25]). These materials offer a green strategy to reuse agricultural and biological waste as an inexpensive and renewable source of sorbent materials [26].

Cyanobacteria, particularly *Arthrospira platensis*, have shown promise as biosorbents in various studies due to their favorable physicochemical properties, including selectivity and high binding affinity. Several researchers have reported the use of *A. platensis* to remove several compounds [27]. Mitrogiannis et al. reported its effectiveness in the biosorption of methylene blue [28], while Markou et al. reported the ejection of Cu^{2+} and Ni^{2+} on *A. platensis* biomass [29]. Similarly, Alprol et al. achieved high removal values using *A. platensis* biomass to remove methyl orange from water [30]. Recently, Diaz et al. reported phosphorus removal from water onto biochar fabricated using a cyanobacteria biomass obtained from a local swamp [31].

Due to the higher amounts of phosphorus delivered to the ambient, along with changes in precipitation around the world, eutrophication is expected to increase during the 21st century [32]. In this context, cyanobacteria biomass could be a very important material to obtain as a sorbent material to remove phosphorus from water. This methodology could solve two problems: (i) higher phosphorous in water, and (ii) bioaccumulation of cyanobacteria in water. However, despite growing interest in the use of *A. platensis* for biosorption, there is limited research on its kinetic and thermodynamic behavior in phosphate biosorption. Therefore, in this work, we study the implementation of *A. platensis* biomass for removing phosphorus from aqueous solutions, with a focus on adsorption efficiency, kinetics, and isothermal behavior.

2. Materials and Methods

2.1. *A. platensis* Cultivation and Biomass Extraction

The cyanobacterium *Arthrospira platensis* (strain SAG 21.99) was cultured in BG-11 medium. The pH of this medium, composed of macro- and micronutrients, was adjusted to a value of 7.4. Cultivation was carried out at a constant temperature of 303 K.

Cell concentrations were monitored every 48 h using a Neubauer hemocytometer (0.1 mm depth) under a binocular optical microscope. The cell density (cells·mL^{−1}) was calculated, until the culture reached its stationary growth phase, using Equation (1):

$$[\text{Cell}] = \frac{\text{cell count} \times 250000}{\text{counting chambers}} \quad (1)$$

where [Cell] denotes cell density, calculated as the total number of cells counted across all chambers of the Neubauer hemocytometer [33]. This data was used to construct the growth curve. After cultivation, approximately 6 L of *A. platensis* wet biomass was harvested by filtration through 13 µm filter paper. The collected biomass was subsequently dried for 48 h at 60 °C. Finally, the sample was characterized through Fourier transform infrared spectroscopy (FTIR), micro-Raman spectroscopy (model NSR 4500 from Jasco, Hachioji-shi, Tokyo), and scanning electron microscopy (SEM, Phenom Pro X).

2.2. Phosphorus Adsorption Study onto Biomass

Phosphorus concentrations were determined according to the 4500-P Standard Method. The persulfate oxidation method was employed to determine phosphorus concentration. Details are reported in [34].

The adsorption capacity of the biomass for phosphorus remotion was investigated through both kinetic and isothermal studies. In the kinetic study, 500 mg of dried biomass was mixed with P solution (25 mg L^{−1}). The system was stirred at 400 rpm, T = 295 K, at a pH = 5.4 for 30 min. For the isothermal adsorption study, we employed the same conditions of the kinetic study with varying P concentrations (5–25 mg L^{−1}). These mixtures were also stirred at 400 rpm under the same temperature and pH conditions for 30 min. We obtained the phosphate adsorption capacity on biomass as follows (Equation (2)):

$$q_t = \frac{((C_o - C_t)V)}{m}, \quad (2)$$

where C_o (mg/L) is the initial concentration, C_t (mg/L) is the P concentration in the solution as a function of time, V (L) is the volume of the system, and m (g) is the amount of biomass. The data were used for modeling the kinetic results.

For the isothermal adsorption study, 500 mg of biomass was similarly mixed with 50 mL of [Phosphorus], changing concentrations between 5 and 25 mg·L^{−1}. These mixtures were also stirred at 400 rpm under the same temperature and pH conditions for 30 min [35].

We obtained the phosphate adsorption on biomass according to Equation (3):

$$q_e = \frac{((C_o - C_e)V)}{m}, \quad (3)$$

where q_e is the amount (mg) of phosphate adsorbed (mg/g biomass) at equilibrium and c_e is the phosphate concentration at equilibrium biosorption–desorption.

3. Results and Discussions

3.1. *Arthrospira Platensis* Growth Curve

Figure 1 shows the growth curve of *A. platensis* obtained in this study. An exponential increase in the cell density was observed up to day 10, corresponding to the period of maximum growth rate. From day 10 to day 15, growth continued but at a gradually decreasing rate, indicating a transition towards the stationary phase. Finally, after day 15, a stabilization of the biomass was observed, suggesting that the algal population reached its load capacity in the culture medium. This growth pattern is consistent with typical microbial growth dynamics, and aligns with previous findings reported for *A. platensis* cultures [36].

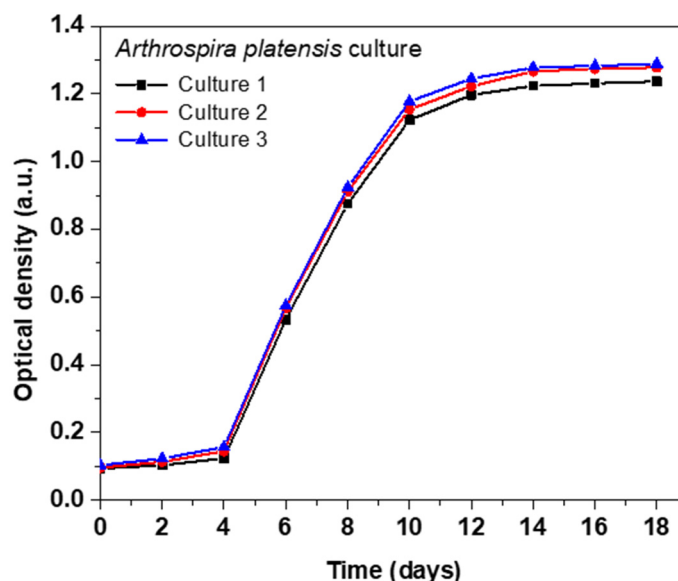


Figure 1. Growth curve of *A. platensis*. Cultures were grown in BG-11 medium with sterile distilled water at pH 7.4 and 303 K. Culture 1 is represented by the black line, Culture 2 by the red line, and Culture 3 by the blue line.

3.2. Spectroscopic Characterization

Figure 2 shows the FTIR and Raman spectra obtained from *A. platensis* biomass. For the FTIR spectrum, several characteristic bands were identified, corresponding to functional groups commonly reported in the literature on microalgae biomass [37]. The broad band located at 3250 cm^{-1} corresponds to the O–H bond, often associated with hydroxyl groups. In the region of $2800\text{--}3200\text{ cm}^{-1}$, additional signals are observed, which can be linked to symmetric and asymmetric stretching of the --CH_3 and --CH_2 groups found in hydrocarbon chains. The peak located at 1715 cm^{-1} is assigned to the C=O stretching, typically associated with the presence of proteins [38], while the peak at 1640 cm^{-1} corresponds to the N–H vibrations of amine group. Furthermore, peaks located between 1030 and 1110 cm^{-1} are associated with aromatic C–H bending and symmetric C–O vibrations [39].

For the Raman spectrum in Figure 2, a very strong vibration at 1073 cm^{-1} , associated with the C–O–C bond, is observed, indicating the presence of carbohydrates, extracellular polysaccharides, and nucleic acids [40]. In the range of $1200\text{--}1500\text{ cm}^{-1}$, signals correspond to C–H and C–N, including those from Amide III structures, reflecting the presence of proteins and lipids. Although weaker, bands above 3000 cm^{-1} are also detectable and may correspond to O–H or N–H stretching vibrations, potentially originating from residual moisture, proteins, or polysaccharides in the dry biomass sample [41].

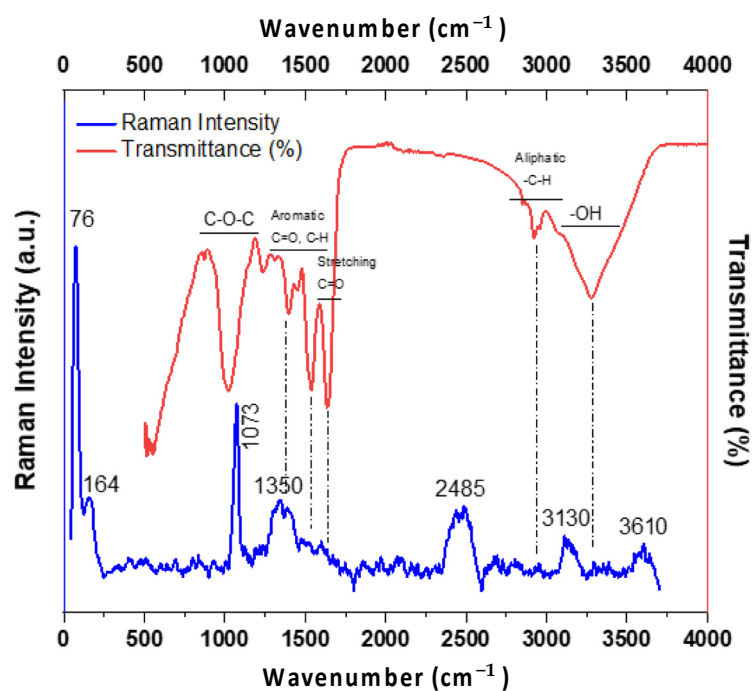


Figure 2. FTIR (red) and Raman (blue) spectra of biomass obtained from *A. platensis*.

3.3. Morphological Characterization

The images of the *A. platensis* biomass at different magnifications are shown in Figure 3. In the low-magnification image (Figure 3a), irregularly shaped particles are observed, with a broad range of the sizes (1–10 μm). This result indicates that the sample morphology is heterogeneous in nature, likely exhibiting fractured or eroded surfaces due to the drying process.

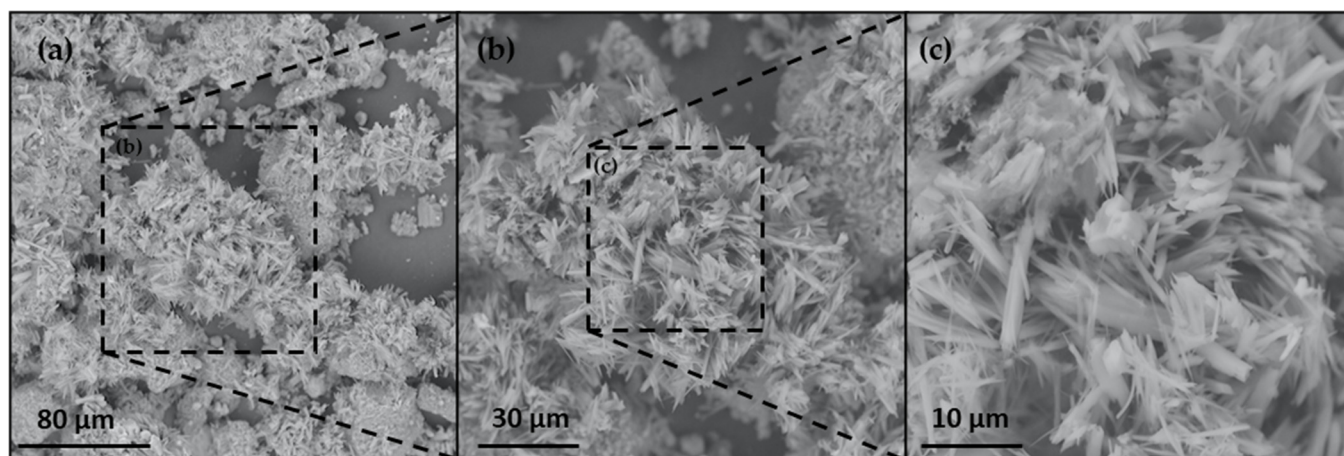


Figure 3. Scanning electron micrographs of biomass obtained from *A. platensis*. Magnification: (a) 1000 $\times$; (b) 2000 $\times$; and (c) 5000 $\times$.

At a higher magnification (Figure 3b,c), the biomass surface reveals rod-like structures of varying lengths. This morphological feature is particularly significant, as the presence of nanorods increases the available surface area for phosphate biosorption. A larger contact area enhances the interaction surface of the sorbent and the adsorbate, which is a desirable property for biosorption-based contaminant removal applications.

3.4. Adsorption Study

Before conducting kinetic and isothermal adsorption experiments, the pH value effect on the phosphorus biosorption efficacy was evaluated (see Figure 4). This result shows that phosphorus biosorption is significantly more effective at lower pH values. Specifically, efficiency of the process decreased from 88% at pH 4.4 to just 7.7% at pH 10.7. It is known that pH affects the electrostatic interaction between ions and the surface of the biomass. This is due to the fact that pH can change the charge of the chemical groups located at the biomass surface. At basic pH, the hydroxyl groups are deprotonated, and negative density on the biomass surface increases. At the same time, the negative charge on phosphate reduces the possibility of electrostatic adsorption in the biomass surface. While at an acidic pH, the biomass surface is less negative, assisting the phosphate adsorption on the biomass surface [42].

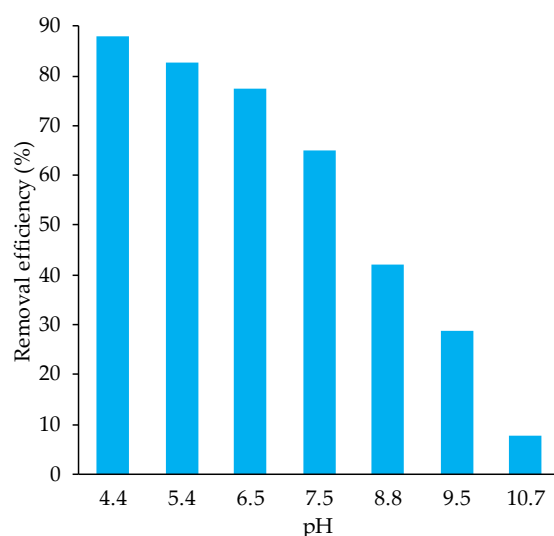


Figure 4. pH effect on the biosorption efficiency of phosphate onto biomass obtained from *A. platensis*.

Furthermore, water purification at pH 4.4 can inhibit other biosystems, which means that nitrification/denitrification processes may potentially be attenuated. However, results shown in Figure 4 indicate that the biosorbent remains effective at pH 6.5, where nearly 80% of phosphate is removed. Under this pH condition, the biosystem could survive. Conducting the biosorbent process under neutral conditions is therefore suitable for phosphate removal without adversely affecting other biosystems. Finally, to achieve complete phosphate removal from water, two options can be implemented: (i) renewing the biosorbent material to continue the removal process, or (ii) employing a coagulation process [43].

3.5. Kinetic Study

Figure 5 shows the kinetic adsorption study of phosphate biosorption onto *A. platensis* biomass. This figure shows that biosorption capacity (q_t) increases quickly, reaching saturation of the surface around 15 min and achieving a maximum biosorption capacity (q_e) of approximately 2.4 mg g^{-1} . The results show that the saturation point is reached after 20 min, indicating a rapid uptake of phosphate ions.

We employed three models to describe the experimental results, according to the information listed in Table 1 [44]. The PSO was suitable to describe results (Table 2). This model establishes that the biosorption process is controlled by chemical interactions where electrostatic interactions are present during the biosorption process. This implies that chemical interactions (e.g., covalent bonding or electron sharing) between ions and chemical groups on the biomass are present during the removal process. Other authors

have reported a PSO model to model the results of the phosphate removal. Manawi et al. reported that phosphorus adsorption on modified biochar followed the pseudo-second order model [45]. Qin et al. reported that phosphorus removal on three different biochar were described by the PSO [46]. This model is frequently employed to fit data results. Table 2 lists some reports when PSO was employed to fit phosphate removal from water.

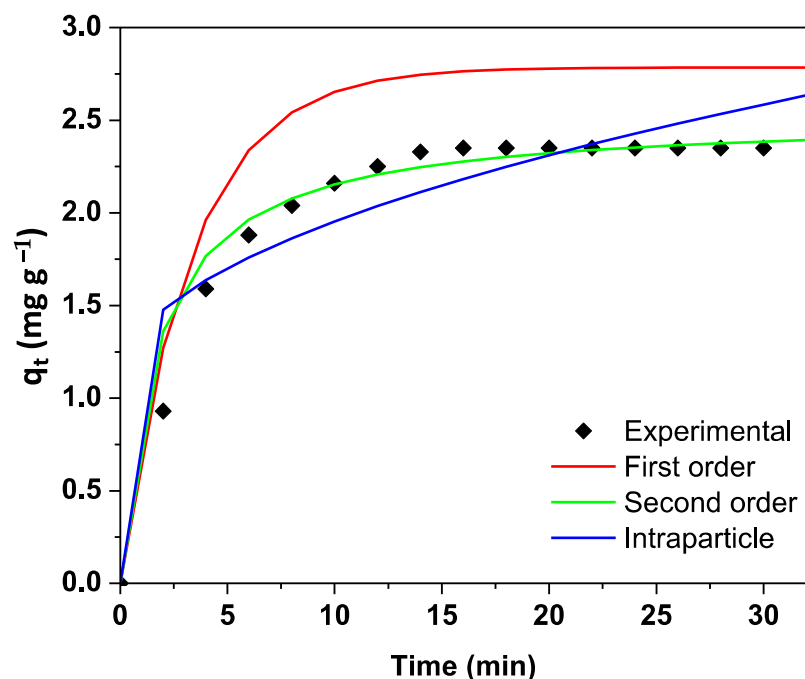


Figure 5. Kinetic fitting of phosphate adsorption onto biomass obtained from *A. platensis*.

Table 1. Mathematical description of adsorption kinetic models employed for fitting the data.

Model	Linear Equation *	Equation Description
Pseudo-first order (PFO)	$\ln(q_e - q_t) = \ln(q_e) - k_1 t$	q_e adsorption capacity at equilibrium, t is time, and k_1 is the rate constant (min^{-1}).
Pseudo-second order (PSO)	$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \left(\frac{1}{q_e}\right) t$	q_t is the equilibrium adsorption capacity and k_2 is the rate constant ($\text{g} \cdot \text{mg}^{-1} \cdot \text{min}^{-1}$).
Intraparticle diffusion	$q_t = k_{id}(t)^{\frac{1}{2}} + c$	k_{id} is the rate constant ($\text{g} \cdot \text{mg}^{-1} \text{min min}^{-1/2}$) and c is constant ($\text{mg} \cdot \text{g}^{-1}$)

* Equation employed to plot Figure 5.

Table 2. Kinetic fitting of phosphate adsorption data on biomass *.

Model	Parameters		
PFO	q_e ($\text{mg} \cdot \text{g}^{-1}$)	k_1 (min^{-1})	R^2
	2.8	1.41	0.9519
PSO	q_e ($\text{mg} \cdot \text{g}$)	k_2 ($\text{g}/(\text{mg} \cdot \text{min})$)	R^2
	2.5	0.233	0.998
Intraparticle diffusion	C $\text{mg} \cdot \text{g}^{-1}$	K_{id} ($\text{g}/\text{mg} \cdot \text{min}$)	R^2
	1.09	0.273	0.716

* Data obtained from Figure 5.

3.6. Isothermal Study

Figure 6 presents the experimental results of the adsorption isotherm. In this study, three isothermal models were employed to describe experimental results, according to the information listed in Table 3 [47].

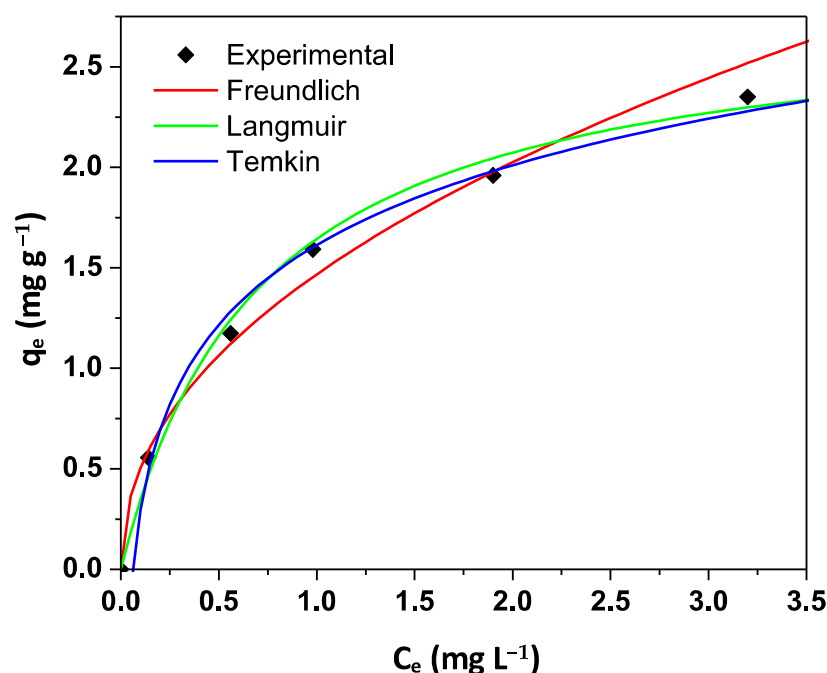


Figure 6. Isothermal fitting of phosphate adsorption onto biomass obtained from *A. platensis*.

Table 3. Mathematical description of isothermal models employed for fitting the data.

Model	Linear Equation *	Equation Description
Langmuir	$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m}$	q_m is the adsorption capacity at equilibrium, t is time, and k_L is constant of model (L·mg ⁻¹). C_e is (is the equilibrium concentration of phosphate (mg·L ⁻¹).
Freundlich	$\ln q_t = \ln K_F + \frac{1}{n} \ln(C_e)$	K_F is constant of model ((mg·g ⁻¹)(L·mg ⁻¹) ^{1/n}) and n is a constant associated with heterogeneity of the surface.
Temkin	$q_e = B \ln(A_T C_e)$	B is the constant of the model and A_T is a constant associated with equilibrium anchoring (L·mg ⁻¹).

* Equation employed for plotting Figure 6.

Table 4 summarizes the isothermal results for each model. According to Figure 6 and Table 4, the Langmuir model suitably described the isothermal results. Results indicate that phosphate adsorption onto the *A. platensis* biomass can be explained by a mechanism of monolayer type, in which the process continues until all active sites on the absorbent are fully saturated by ions to form the monolayer. This monolayer model has been applied to describe the phosphorus removal. Liao et al. employed this model to describe the phosphate adsorption on modified pineapple biochar [48]. Other authors have reported that multilayer sorption can describe the phosphate adsorption. Table 5 compares some reports about phosphorus removal from water onto different materials. Others authors applied the Freundlich model to describe phosphorus removal onto biochar [49]. However,

due to the fact that the mechanism of phosphate adsorption on biomass can involve more than one step (e.g., surface precipitation, ionic exchange, electrostatic interactions) [50], the type of mechanism in the isothermal sorption process could depend on the sorbent source and the method to obtain sorbent material [51].

Table 4. Isothermal fitting of phosphate adsorption data on biomass **.

Model	Parameters		
Langmuir	q_{max} (mg/g)	K_L (L·mg ⁻¹)	R^2
	2.8	1.41	0.992
Freundlich	$K_F(\text{mg} \cdot \text{g}^{-1})(\text{L} \cdot \text{mg}^{-1})^{1/n}$	$1/n$	R^2
	1.47	0.46	0.986
Temkin	B_t (L·mg ⁻¹)	K_T (L·g ⁻¹)	R^2
	0.57	16.7	0.988

** Data obtained from Figure 6.

The results listed in Table 5 are comparable to those reported in previous studies on phosphate adsorption employing different adsorbent materials. For example, Jung et al. reported $q_e = 3.01 \text{ mg g}^{-1}$ in phosphorus adsorption using biochar derived from peanut shells [52]. Similarly, Zhu et al. reported a $q_e = 3.08 \text{ mg g}^{-1}$ in the phosphate removal using a composite material consisting of Fe₂O₃/Fe₃O₄/bamboo biochar [53].

Table 5. Sorption efficacy for phosphorus remotion from water onto different carbonaceous materials.

Sorbent Material	Adsorption Capacity (mg g ⁻¹) ¹	Isothermal Model	Kinetic Model
Biochar cyanobacteria [31]	5.5	Langmuir	SS
Biochar pineapple [48]	3.7	Langmuir	SS ²
Biochar/sewage sludge [54]	0.7–1.2	NR ³	NR
Biochar/pine sawdust [55]	2.0	NR	NR
Fe-biochar modified [56]	0.56	NR	NR
Iron-loaded tannin gel [57]	2.7	Freundlich	NR
Cyanobacteria biomass (this work)	2.8	Langmuir	SS

¹ Data obtained from reports in literature. ² Second order. ³ Not reported.

4. Conclusions

In this study, biomass was obtained from *A. platensis* and evaluated for its potential in phosphate biosorption. Characterization by FTIR, Raman, and SEM revealed a chemical composition and surface morphology conducive to interactions with phosphate ions. The biomass consisted of heterogeneous fragments with fractured, rough surfaces and visible cavities or pores, indicating high surface porosity. The phosphate removal efficiency was strongly influenced by pH, with maximum biosorption observed under acidic conditions and rapid uptake reaching equilibrium within a short time.

The PSO model provided the best fit, indicating that chemical interactions are the driven forces in the sorption process. Furthermore, the Langmuir model was suitable for describing the adsorption behavior, suggesting monolayer coverage on a homogeneous surface. Overall, *A. platensis* biomass demonstrated promising potential as an effective sorbent for phosphorus removal applications.

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writing—review and editing, Y.B., C.D.-U., W.V., J.E.D. and E.M.-V.; supervision, C.D.-U. and W.V.; project administration, C.D.-U., W.V. and E.M.-V.; funding acquisition, C.D.-U., W.V., J.E.D. and E.M.-V. All authors have read and agreed to the published version of the manuscript.

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