Kinetic Modeling of Phosphate Adsorption onto Algae-Saturated Chitosan Composites from Aqueous Solution under Batch Conditions

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| ***KEYWORDS*** |  | ***ABSTRACT*** |
| Adsorption kinetics,  Algae-saturated chitosan composite, Batch adsorption, Biosorbent, Phosphate removal  Spirulina platensis,  Pseudo-first-order model, Pseudo-second-order model,  Wastewater treatment |  | Phosphate contamination in water bodies has emerged as a major environmental concern due to its role in eutrophication and water quality degradation. This study investigates the phosphate adsorption behaviour of algae-saturated chitosan composites synthesised using *Spirulina platensis* under batch experimental conditions. The adsorption performance was evaluated at an initial phosphate concentration of 50 mg L⁻¹, using 1.0 g L⁻¹ of the composite, at ambient temperature and pH 5.65 ± 0.1. The maximum phosphate removal efficiency reached 24.04 %, with adsorption equilibrium achieved within 120 minutes. Kinetic modelling indicated that the pseudo-second-order model (R² = 0.983) provided a better fit than the pseudo-first-order model (R² = 0.737), suggesting that chemisorption governs the adsorption process. The equilibrium adsorption capacity (*qe​*) calculated from the pseudo-second-order model was 13.51 mg g⁻¹, closely matching the experimental value of 12.04 mg g⁻¹. These results demonstrate the synergistic potential of algal biomass and chitosan as a low-cost, biodegradable, and efficient biosorbent for phosphate removal from aqueous solutions. The study offers a promising approach for developing sustainable materials for water purification applications. |
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1. Introduction

Phosphate contamination in aquatic environments has become a pressing global concern due to its critical role in accelerating eutrophication, which leads to excessive algal blooms, oxygen depletion, and loss of aquatic biodiversity (Devlin & Brodie 2023). The increasing anthropogenic discharge of phosphates from domestic wastewater, agricultural runoff, and industrial effluents has made the development efficient and sustainable remediation techniques a high priority (Akhtar, **et al.,** 2021). Among various removal strategies, adsorption has been widely recognized as an effective, low-cost, and environmentally benign approach for phosphate removal from aqueous systems (Velusamy, **et al.,** 2021). Natural biopolymers such as chitosan, derived from chitin, have gained significant attention owing to their high surface area, functional groups (e.g., –NH₂ and –OH), biodegradability, and non-toxicity (Ahmedd, 2025). However, unmodified chitosan often exhibits limited adsorption capacity for anionic contaminants like phosphate due to electrostatic repulsion at neutral pH (Wujcicki, & Kluczka, 2023).

To overcome the limitations of unmodified chitosan, composite materials integrating chitosan with other bio-adsorbents have been developed to enhance binding affinity, structural stability, and overall adsorption performance (Ahmedd, 2025). Algal biomass, particularly microalgae and cyanobacteria, has emerged as a promising additive due to its high phosphate uptake capacity, abundant functional groups, and intrinsic nutrient-binding properties (Shuman, 2016).). The integration of algal biomass into chitosan matrices creates a synergistic effect, improving phosphate adsorption through mechanisms such as ion exchange, ligand binding, and electrostatic interactions (Zhao, et al., 2024).

Batch adsorption experiments remain a fundamental tool for understanding solute–adsorbent dynamics, especially in evaluating the rate and mechanism of phosphate removal under controlled conditions (Wu, et al., 2019). Kinetic modelling of these systems—using pseudo-first-order, pseudo-second-order, and intraparticle diffusion models—facilitates mechanistic interpretation of adsorption behaviour, distinguishing between surface adsorption, chemisorption, and pore diffusion processes (Mohamed, et al., 2024; Oktor, et al., 2023)

Despite progress in biosorbent development, limited studies have addressed the kinetics of phosphate removal using algae-saturated chitosan composites, particularly under varying batch conditions (Fierro, et al., 2008 ; Vasilieva et al., 2025). Therefore, the present study aims to develop and evaluate the phosphate adsorption kinetics of a novel bio-composite comprising chitosan and algal biomass, to assess its potential for practical application in water treatment systems.

2. Materials and Methods

**2.1 Materials**

Chitosan (molecular weight: 3,800–20,000 Da; degree of deacetylation ≥ 75% HiMEDIA), glacial acetic acid (100%; SIGMA), sodium hydroxide (NaOH, pellets, HiMEDIA), and lyophilized powder of *Spirulina platensis* were procured from certified suppliers and used without further purification. All reagents were of analytical grade. Double-distilled water was used for all solution preparations.

**2.2 Preparation of Algae-Saturated Chitosan Composites**

The algae-saturated chitosan composites were prepared following the modified method of Udoetok et al., (2024). Briefly, 2.0 g of chitosan flakes were dissolved in 100 mL of 1% (v/v) glacial acetic acid solution under vigorous magnetic stirring to obtain a uniform hydrogel. The solution was left undisturbed for 24 hours to allow complete dissolution. The resulting chitosan hydrogel was then extruded dropwise using a 2-mm syringe needle into a 0.5 M NaOH coagulation bath to form spherical beads. These beads were immersed in an aqueous stock solution of *Spirulina platensis* algae and stirred continuously for 6 hours to allow thorough algal absorption and saturation. After saturation, the beads were transferred again into a fresh 0.5 M NaOH solution and allowed to stand for 24 hours to complete the coagulation process. Finally, the beads were washed repeatedly with distilled water until the rinse water reached neutral pH.



**Picture 1-Algal-saturated chitosan beads**

**2.3 Phosphate Analysis**

The concentration of phosphate in aqueous samples was determined spectrophotometrically using the molybdate-ascorbic acid method as described by Habibah, **et al.,** (2018). Absorbance was measured at 690 nm using a UV-Vis spectrophotometer. Calibration was performed using standard phosphate solutions prepared from KH₂PO₄.

**2.4 Adsorption Kinetics Experiment**

Batch adsorption kinetic experiments were performed to study phosphate removal by the algae-saturated chitosan composites. A fixed phosphate concentration of 50 mg L-1 (prepared using KH₂PO₄) was used with a solution volume of 50 mL. The adsorbent dosage was maintained at 1.0 g L-1. The experiments were conducted at ambient temperature (~25 ± 2°C), under continuous shaking at 250 rpm, and pH was maintained at 5.65 ± 0.1 without further adjustment.

At predetermined time intervals (0–120 minutes), aliquots were withdrawn, filtered, and analysed for residual phosphate concentration. The adsorption capacity (*qt*)​ and phosphate removal efficiency (%) were calculated using the following equations:-

1. **Phosphate adsorption capacity (*qt​*)**
2. **Phosphate removal efficiency (%) =**

Where, *qt*: adsorption capacity at time (mg g-1), *Co*: Initial phosphate concentration (mg L-1), *Ct*: Phosphate concentration at time t (mg L-1), V: volume of phosphate adsorbate (L), m: mass of adsorbent (g)

**2.5 Kinetic Modeling**

To understand the adsorption mechanism and rate-controlling steps, two kinetic models were applied to the experimental data:

1. **Pseudo-first order** (Lagergren, 1898): **-**
2. **Pseudo-first order** (Ho & McKay, 1999): **-**

Where, *qe*: adsorption capacity at equilibrium (mg g-1), *qt* ​: adsorption capacity at time t (mg g-1), *k1*​: pseudo-first-order rate constant (min-1), *k2*: pseudo-second-order rate constant (g mg-1·min), t: time(min)The model that best fit the experimental data was evaluated based on the coefficient of determination (R²), as suggested by Hernandez (2023).

**3.0 Results & Discussion**

**3.1 Phosphate Adsorption Profile**

The time-dependent phosphate adsorption behaviour of the algal-saturated chitosan composite is shown in Fig. 1. and Table 1



**Fig. 1: Graph indicating time-dependent phosphate adsorption behaviour of the algal-saturated chitosan composite**

A rapid initial increase in phosphate adsorption was observed during the first 30 minutes, reaching approximately 16.8 %. Thereafter, the adsorption rate slowed and approached a plateau at around 120 min., indicating the approach to adsorption equilibrium. The maximum removal reached approximately 24.08 %, confirming the potential of algal-functionalized chitosan for phosphate sequestration from aqueous media under batch conditions. The phosphate adsorption behavior of algal-saturated chitosan composites, as observed in the kinetic study, reveals important insights into the mechanism and efficiency of the biosorbent system. The initial rapid uptake of phosphate within the first 30 minutes can be attributed to the abundant availability of active sites on the chitosan matrix and the algal surface, facilitating surface sorption. This is a typical characteristic of biosorbents, where diffusion to external surfaces dominates the early stages of adsorption.The gradual plateauing of adsorption observed after 60 minutes suggests a transition from surface binding to slower intraparticle diffusion or saturation of binding sites (Crini & Badot, 2008). At this stage, the reduced availability of active sites, previously adsorbed phosphate ions, may limit further uptake (Bhatnagar & Sillanpaa, 2011; Wujcicki & Kluczka, 2023)**.**

**3.2 Kinetic Modelling**

To understand the adsorption mechanism and to determine the rate-controlling steps, the experimental data were fitted using pseudo-first-order and pseudo-second-order kinetic models. The calculated values for adsorption capacity (*qt*​), log(*qe−qt*​), and *t/qt* are provided in Table 1.

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| **Time** | **Parameters** | | |
| ***qt***  **(mg g-1)** | **Log(*qe-qt*)** | ***t/qt***  **(min. g mg-1)** |
| **0** | 0.211 | 1.072 | 0 |
| **5** | 3.190 | 0.946 | 1.567 |
| **10** | 4.417 | 0.882 | 2.263 |
| **15** | 6.812 | 0.718 | 2.201 |
| **30** | 8.389 | 0.562 | 3.575 |
| **45** | 9.732 | 0.363 | 4.623 |
| **60** | 10.286 | 0.243 | 5.832 |
| **75** | 11.513 | -0.278 | 6.514 |
| **90** | 11.951 | -1.053 | 7.530 |
| **105** | 12.039 | -3.825 | 8.721 |
| **120** | 12.040 | **----** | 9.966 |

**Table 1: Kinetics of phosphate adsorption parameters over time**

**3.3 Pseudo-First-Order Kinetics**

The linear regression of log (*qe−qt*​) vs. time (Fig. 2 and Table 2) yielded a moderate correlation coefficient (R² = 0.737), suggesting that this model only partially explains the adsorption process. The estimated equilibrium adsorption capacity *qe​* was found to be 27.03mg g-1, which deviated significantly from the experimental values, further confirming the poor fit.



**Fig. 2: Graph indicating the linear regression of log(*qe−qt*​) vs. time**

**3.4 Pseudo-Second-Order Kinetics**

In contrast, the pseudo-second-order model (Fig. 3 & Table 2) provided a much better linear fit with a high correlation coefficient (R² = 0.983). The calculated equilibrium adsorption capacity *qe*​ was 13.51mg g-1 which is much closer to the experimentally observed value (12.04 mg g-1), supporting the model's validity. The pseudo-second-order kinetic model is based on the idea that chemisorption controls the rate-limiting phase, which involves the sharing or exchange of electrons between the adsorbate and the adsorbent surface (Mohamed et al., 2024). In this study, the improved fit implies that functional groups like –NH₂ and –OH on the chitosan backbone and algal biomass are very important for making strong phosphate–ligand interactions. This is in accordance with recent research that showed modified biopolymer-based adsorbents had comparable kinetic patterns and chemisorption dominance (Mohamed et al.; Velusamy et al., 2023).The observed match between the experimental and theoretical *qₑ* values further validates the model and implies uniform active sites and a consistent adsorption mechanism across the biosorbent surface (Zain et al. (2023)). Additionally, similar high-performance kinetics have been reported for other chitosan-based and algal-enhanced bio-composites, where phosphate uptake efficiency was driven by the availability of electron-donating groups and the structural porosity facilitating accessibility to these active sites (Udoetok et al., 2024). These findings collectively indicate that the pseudo-second-order model can effectively capture the kinetics of biosorption systems where chemisorption dominates, making it a reliable tool for predicting phosphate removal behaviour in practical water treatment scenarios.



**Fig. 3: Graph indicating linear regression of t/qt (min g mg-1) vs. time**

Conversely, the pseudo-first-order model, which is often suited for physisorption processes, exhibited a poor fit and overestimated the adsorption capacity (27.03 mg g-1), indicating it is not appropriate for this system. This discrepancy could be due to the complex nature of phosphate binding to multiple active sites present in both chitosan and algal components, which involves not only electrostatic attraction but also ligand exchange and hydrogen bonding (Shi et al., 2011 Munteanu et al., 2025). Thus, the findings suggest that **algae-enriched chitosan composites** can act as promising biosorbents for phosphate removal in wastewater treatment.

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| **Kinetics** | **Algal-Saturated Chitosan Composite** | |
| **Parameters** | **Value** |
| **Pseudo-first order** | Intercept | 1.432 |
| Slope | 0.033 |
| *k1* (min⁻¹) | 0.075 |
| *qe*(mg g-1) | 27.03 |
| R2 | 0.737 |
| **Pseudo-second order** | Intercept | 1.04 |
| Slope | 0.074 |
| *k2*  (g mg-1·min) | 0.005 |
| *qe* (mg g-1) | 13.51 |
| R2 | 0.983 |

**Table 2: Correlation coefficient and other parametric values of the kinetics model**

**4. Conclusion**

This study demonstrates the effective use of algae-saturated chitosan composites for phosphate removal from aqueous solutions under batch conditions. The adsorption process exhibited a rapid uptake phase followed by equilibrium attainment within 120 minutes, with a maximum removal efficiency of approximately 24.0 %. Kinetic modeling revealed that the pseudo-second-order model best described the adsorption behavior, suggesting that chemisorption is the dominant mechanism, likely involving functional groups from both chitosan and *Spirulina platensis*. The high correlation coefficient (R² = 0.983) and close agreement between calculated and experimental adsorption capacities further confirm the model's validity. These findings highlight the synergistic potential of combining chitosan and algae biomass to develop eco-friendly, low-cost, and efficient biosorbents for phosphate removal in wastewater treatment applications.

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