

Article

Phosphorus Removal from Aqueous Solutions Using Biochar Derived from Cyanobacterial Biomass

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Abstract: High phosphorus (P) content and eutrophication are chemically and biologically related processes. Reducing phosphorus levels in water is essential for controlling eutrophication. In this study, biochar was produced from cyanobacteria biomass and evaluated as an adsorbent for phosphorus removal from water. The cyanobacterial biomass was collected from a local swamp in the “Departamento del Atlántico”, Colombia, and heated at 350 °C for 2 h to induce partial carbonization. The resulting biochar was characterized using vibrational spectroscopy and scanning electron microscopy (SEM/EDS). The adsorption capacity of cyanobacteria-derived biochar was assessed through kinetic and isothermal adsorption studies. The kinetic analysis revealed a maximum adsorption capacity of 5.51 mg/g and a rate constant of 0.084 g mg^{−1} min^{−1}, with the pseudo-second-order model providing the best fit. The isotherm analysis showed that the Langmuir model accurately described the adsorption process, with an adsorption constant (K_L) of 0.360 L mg^{−1}, suggesting monolayer adsorption on the biochar surface. These results confirm that biochar obtained from cyanobacterial blooms is an effective and sustainable material for phosphorus removal from aqueous solutions, offering a promising strategy for nutrient pollution control and environmental remediation.

Keywords: adsorption; phosphorus; water pollution; cyanobacteria; biochar



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1. Introduction

Different factors, such as population growth, poor management, and climate change, have negatively affected water quality in many regions [1]. One of the significant global challenges in the mid-term is access to potable water. The World Health Organization (WHO) estimates that 2 billion people live in countries with limited access to clean drinking water [2]. Anthropogenic activities, such as the chemical and pharmaceutical industries and agriculture, contribute to the dumping of large quantities of organic and inorganic toxic compounds, which further degrade water quality and increase the health risks associated with these substances [3]. Various pollutants, including organic compounds, hormones,

antibiotics, dyes, plastics, and phosphorus, continue to accumulate in water systems. Among these pollutants, phosphorus plays a crucial role in various production systems worldwide (e.g., detergent production [4], steel industry [5], pharmaceutical [6], agriculture, and animal feed [7]).

The scarcity of water resources and their increasing deterioration have made the presence of phosphates as water pollutants a topic of growing concern in recent years. The rise in phosphate ion concentrations is a direct consequence of anthropogenic activities related to industrial and household waste. When present in excessive quantities, phosphates can promote the overgrowth of algae and other organisms, leading to pollution and eutrophication processes [8]. Phosphates act as a nutrient for algae growth; thus, when their concentration increases, algae proliferate excessively. This excessive growth can deplete oxygen levels in water, leading to the uncontrolled growth of organic matter, which in turn accelerates decomposition and ultimately results in eutrophication [9]. During this process, the accumulation of plants and cyanobacteria occurs. The decomposition of these species negatively affects pH levels and aquatic species in the environment. Hypoxia from effluents and disruption of trophic ecosystems can be caused by cyanobacteria species [10].

Managing eutrophication involves reducing phosphorus concentrations in aquatic systems. In recent decades, sorption has become an efficient strategy for removing phosphorus from wastewater. Various solids have been employed as adsorbents for phosphorus removal from water, including (i) active carbon [11], (ii) biochar [12], (iii) metal oxides [13], (iv) metal–organic framework (MOFs) [14], (iv) nanoparticles [15], (v) hydroxides [16], and (vi) clays [17]. Among these, biochar is an attractive option due to its low cost, abundance, and potential to mitigate the negative impact of agricultural waste. Biomass is gaining popularity as a renewable energy source due to its environmental sustainability [18,19]. Traditional natural waste can be used to produce biochar, and various microbial biomass (e.g., cyanobacteria, algae) can serve as a potential biochar source. Several metal ions have been removed from water using biochar derived from microalgae [20]. Azam et al. used algal biomass for wastewater treatment [21]. Moreover, biochar has been successfully used to remove phosphorus from wastewater [22]. Chen et al. reported a phosphorus removal capacity of 1.2 mg P g^{-1} using biochar obtained from orange peel treated with iron [23]. Melia et al. reported a phosphorus removal capacity ranging from $0.7\text{--}1.2 \text{ mg P g}^{-1}$ using biochar derived from sewage sludge [24]. Shyam et al. presented a review on the challenges, commercialization, and future perspectives of using biomass as a source for hydrochar and biochar production to recover phosphates from wastewater [25].

The Malambo Swamp, an important water source located in the “Departamento del Atlántico”, Colombia, has recently exhibited high levels of phosphates, resulting in significant cyanobacteria blooms. This situation highlights the urgent need to address the dual problem of cyanobacterial blooms and high phosphate concentrations, both of which negatively impact the biodiversity of the Malambo Swamp. In this study, cyanobacteria collected from the swamp were used to produce biochar for phosphorus removal from contaminated water. The physicochemical properties of the biochar were further investigated using techniques such as vibrational spectroscopy, scanning electron microscopy (SEM), and the adsorption capacity of cyanobacteria biochar in removing phosphorus from water. These analyses enabled the evaluation of the biochar’s effectiveness in removing phosphorus and its potential role in mitigating eutrophication within the Malambo Swamp.

2. Materials and Methods

2.1. Cyanobacteria Biomass Collection and Culture

The samples were collected from the Malambo Swamp, located on the left bank of the Magdalena River ($10^{\circ}85'53''$ north latitude and $74^{\circ}75'64''$ west longitude). Sampling

was conducted in June 2024, during a single working day, with an average maximum temperature of 32 °C and an average humidity of 80%. The cyanobacteria biomass was cultured in a BG-11 medium. Figure S1 shows images of the cultures, and further details of this procedure can be found in a previous study [26].

2.2. Biochar Synthesis and Characterization

After cultivating the cyanobacteria, 6 L of wet biomass was filtered using a 14 µm paper filter, and the resulting solid was dried at 40 °C for 24 h.

Figure S2 shows an image of the dried cyanobacteria biomass. Initial attempts to use the dried cyanobacteria as an adsorbent for phosphorus removal from aqueous solutions were unsuccessful because the cyanobacteria contained phosphorus within its structure. As a result, using the dried biomass as an adsorbent led to the release of phosphorus into the solution. Therefore, only cyanobacteria-derived biochar was used as the adsorbent material for adsorption studies.

For biochar production, 1.0 g of dried cyanobacterial biomass was dispersed in 100 mL of a 0.1 M dibasic ammonium citrate solution. The mixture was stirred at 60 °C for 1 h to facilitate interaction between the citrate and biomass. The material was then filtered to separate the solids, which were subsequently dried at 105 °C for 2 h. Finally, it was exposed to ambient air, then heated at 350 °C for 2 h to induce partial carbonization, enhancing the structural and chemical properties of the biochar (see Figure S3). The physical–chemical properties of the materials were determined through scanning electron microscopy (SEM) and Fourier Transform infrared spectroscopy (FTIR).

2.3. Phosphate Quantification

Since phosphorus is combined with organic matter, a suitable digestion method was employed. The persulfate oxidation method was chosen for its efficiency and simplicity, which make it one of the most widely used approaches. The 4500-P standard method for phosphorus determination outlines a procedure that involves sample digestion to convert all forms of phosphorus, whether organic or inorganic, into dissolved orthophosphate—the measurable fraction [27].

During the digestion process, persulphate is activated by ultraviolet (UV) digestion, which facilitates the oxidation of phosphorus and its conversion into orthophosphates. The process begins in a highly alkaline medium (pH > 12) and becomes acidic at the final stage. The dissolved orthophosphate produced is then quantified using colorimetric methods, allowing for accurate determination of the total phosphorus concentration in the sample. This procedure ensures the complete release of phosphorus and its transformation into a measurable form, thereby optimizing the analysis for various sample types [28]. Phosphorus concentrations were quantified as phosphate by spectrophotometry, applying the Lambert–Beer law at $\lambda = 880$ nm.

2.4. Adsorption Study

The adsorption capacity of cyanobacteria-derived biochar (biochar) for phosphorus removal from water was investigated. The experiments included evaluating the effects of pH (4, 6, 8, 10, and 12) and biochar dosage (10–80 mg) on phosphorus adsorption.

In the kinetic study, 50 mg of biochar was added to a beaker containing 50 mL of a phosphate solution (10 mg L^{-1}). The suspension was stirred at 200 rpm at 298 K, with the pH adjusted to 6, for 60 min. For kinetic modeling, the pseudo-first-order model (SFO), pseudo-second-order model (SSO), and intraparticle diffusion model were applied [29,30]. For the adsorption isotherm study, the following procedure was followed: 50 mg of biochar was added to containers with 50 mL of a PO_4^{3-} solution at different concentrations ($5\text{--}30 \text{ mg L}^{-1}$). We stirred the system at 100 rpm and the pH = 4.2 for 60 min. In the

isothermal modeling, we employed three adsorption models: (i) the Langmuir isotherm, (ii) the Freundlich isotherm, and (iii) the Temkin isotherm models, according to [31,32].

3. Results and Discussion

3.1. Spectroscopic Characterization

Figure 1 shows the FTIR spectra of both dried cyanobacteria and the cyanobacteria biochar obtained after the pyrolysis process. The broad band observed between 3200 and 3600 cm^{-1} is attributed to O–H bonds, which are characteristic of alcohols or phenols. Bands in the 2800–3000 cm^{-1} range correspond to the asymmetric and symmetric stretching vibrations of C–H bonds in aliphatic chains. The band located in the 1600–1700 cm^{-1} region is associated with the stretching C=O groups, while the band between 1500 and 1600 cm^{-1} corresponds to C=C vibrations in aromatic rings. The signal around 1415 cm^{-1} can be attributed to carboxylate groups (–COO–) [33]. Bands located between 1200 and 1500 cm^{-1} can be associated with C–H and C–O bonds, while vibrations of C–O–C or C–O bonds are detected within the 1000–1200 cm^{-1} range. Additionally, aromatic C–H and symmetric C–O stretching vibrations are found between 1030 and 1110 cm^{-1} [34]. A comparison between the dried cyanobacteria and biochar reveals a reduction in the intensity of most signals. This reduction is likely due to dehydration and depolymerization reactions, which contribute to the loss of polar functional groups and the formation of aromatic and graphitic structures [35].

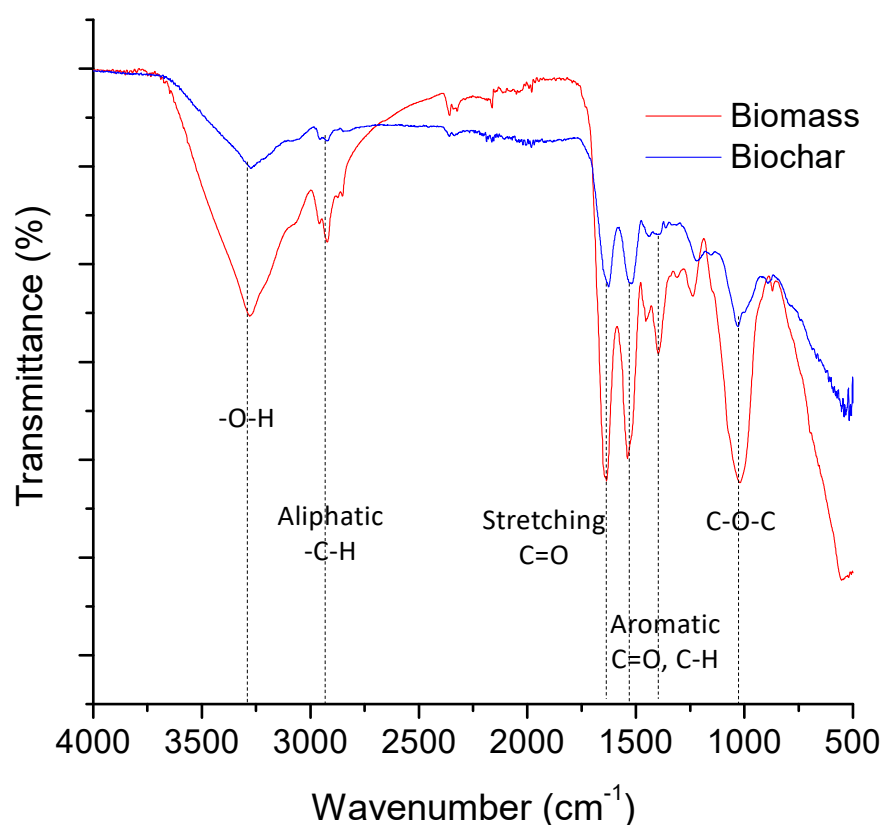


Figure 1. FTIR spectra of dried biomass (red) and cyanobacteria biochar (blue), showing their characteristic peaks.

3.2. Morphological Characterization

Figure 2 shows the SEM images of biomass and biochar derived from cyanobacteria. In the cyanobacterial biomass (see Figure 2a), particles of irregular shape with sizes ranging from a few micrometers to tens of micrometers are observed. This variation in size and shape indicates that the biomass consists of heterogeneous fragments.

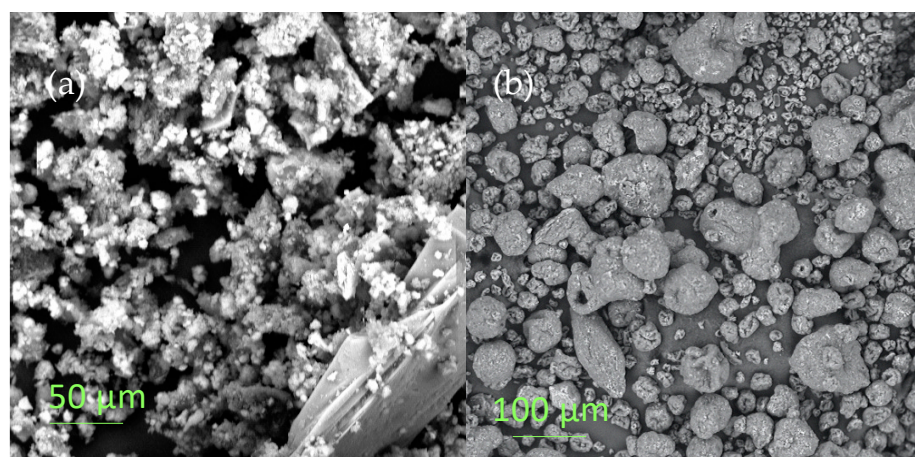


Figure 2. Scanning electron micrographs of (a) cyanobacteria biomass and (b) cyanobacteria biochar.

After the pyrolysis process, the biochar (Figure 2b) exhibits particles with rough surfaces and visible cavities or pores, along with fractured or eroded surfaces, which could be a consequence of the production process. Figure 2b also shows a mixture of large and small particles. The smaller particles may contribute to greater packing density, while the larger ones facilitate the creation of macro- or mesoporous channels, improving the diffusion of liquids or gases through the material [36]. Table 1 summarizes the elemental composition of the biomass and biochar, determined through EDS analysis. The EDS results indicate that molar O/C and (O + N)/C ratios decrease after the pyrolysis process, suggesting the formation of carbonized structures and the development of aromatic and graphitic frameworks. This change in material composition is consistent with the FTIR results (see Section 3.1). Moreover, this change can improve the versatility of the interaction between the biochar surface and phosphorus species. As an anionic species, phosphorus can readily interact with functional groups on the biochar surface through mechanisms such as electrostatic attraction and hydrogen bonding (e.g., hydroxyl and carboxyl groups) [37]. Additionally, other processes, such as inter-particle diffusion, may also occur during adsorption onto the biochar [38].

Table 1. Elemental composition analysis of materials.

Sample	C (%) ¹	O (%) ¹
Biomass	5.0	53.6
Biochar	53.70	21.50

Note(s): ¹ data obtained from EDS assay.

3.3. Study Adsorption Parameters

Figure 3 shows the effect of pH and biochar load on phosphorus removal. The results indicate that phosphate removal is more efficient under acidic conditions, with removal rates of 56.8% at pH 4.2 and 51.5% at pH 6.4. In contrast, under alkaline conditions (pH = 12.3), removal efficiency drops to just 8.5%. Figure 3a suggests that the chemical and physical processes involved in phosphate removal (e.g., electrostatic interactions, diffusion) are more favorable in acidic media. Changes in pH can influence the electrostatic interactions between phosphorus and biochar [39]. The pH value affects the surface charge of the adsorbent. Under alkaline conditions, chemical groups on the biochar surface (e.g., hydroxyl and carboxyl) can be deprotonated, and the biochar surface becomes negatively charged. Simultaneously, phosphate species exhibit increased negative charge density in alkaline environments, which leads to electrostatic repulsion and, consequently, reduced phosphate adsorption [40]. In contrast, at acidic pH values, both the biochar surface

and phosphate species carry lower negative charge density, which promotes phosphate adsorption, as shown in Figure 3a [41]. A hypothetical diagram depicting phosphate sorption onto biochar is shown in Figure S4. Other studies have reported that biochar generally has a negatively charged surface, except under acid conditions [42].

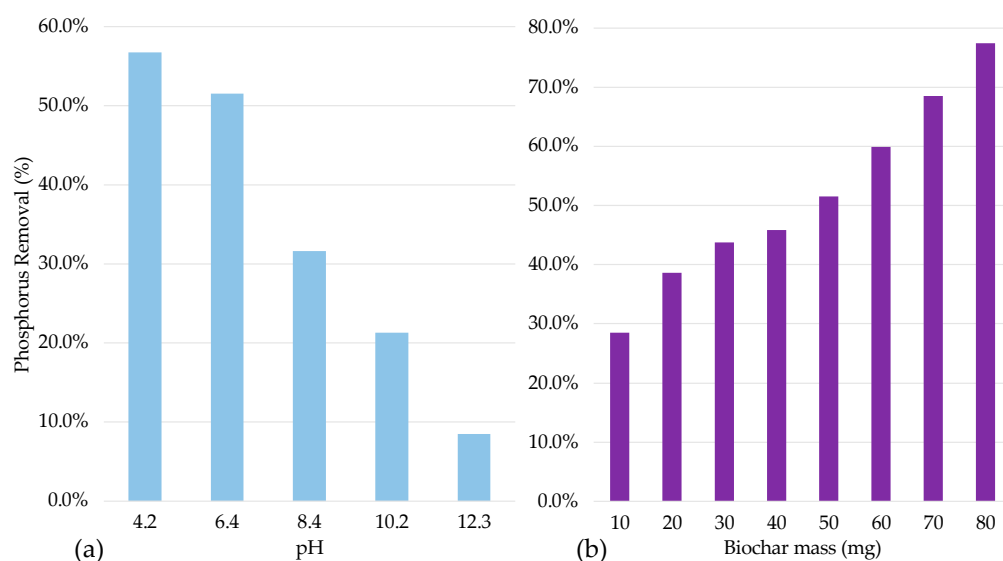


Figure 3. Effect of (a) pH and (b) biochar load on phosphorus removal (P concentration = 10 mg L⁻¹; stirring rate = 200 rpm; temperature = 298 K).

Additionally, the effect of biochar load on phosphorus removal efficiency was evaluated over a range of 10–80 mg. The results show that the final phosphate concentration decreases as the amount of cyanobacteria mass increases, indicating that larger amounts of biochar adsorbed more phosphates. The removal efficacy increased progressively, reaching a maximum of 77.4% with 80 mg of biochar. This result agrees with expectations, considering that as more active sites become available on the cyanobacteria surface for the adsorption process, a greater number of phosphates can be adsorbed on the surface [43].

3.4. Results of Adsorption Study

Figure 4a shows the adsorption capacity (q_t) as a function of time (t). The results show that q_t increases rapidly at the beginning of the process, reaching a steady state around 40–50 min, with a maximum adsorption capacity (q_e) of approximately 5.51 mg PO₄³⁻/g. The curve reflects a high initial effectiveness, which gradually decreases as the system approaches saturation. The results suggest that the saturation point is reached after approximately 30 min. Kinetic modeling results indicate that the pseudo-second-order model provides the best fit to the experimental data (see Table 2), indicating that this model better describes the kinetics of the adsorption process, probably controlled by chemical interactions between the adsorbate and adsorbent rather than solely by the diffusion mechanism. The kinetic analysis suggests that chemisorption is the dominant interaction during phosphate adsorption, where electrostatic interactions play a significant role in the adsorption process. This model has been previously reported in several studies as the most suitable for describing the removal of various pollutants using different types of biochar [44–46]. Moreover, these results align with other studies on phosphate removal using carbon-based materials. For instance, Jung et al. reported that the pseudo-second-order model accurately described phosphate adsorption on biochar derived from peanut shells [47].

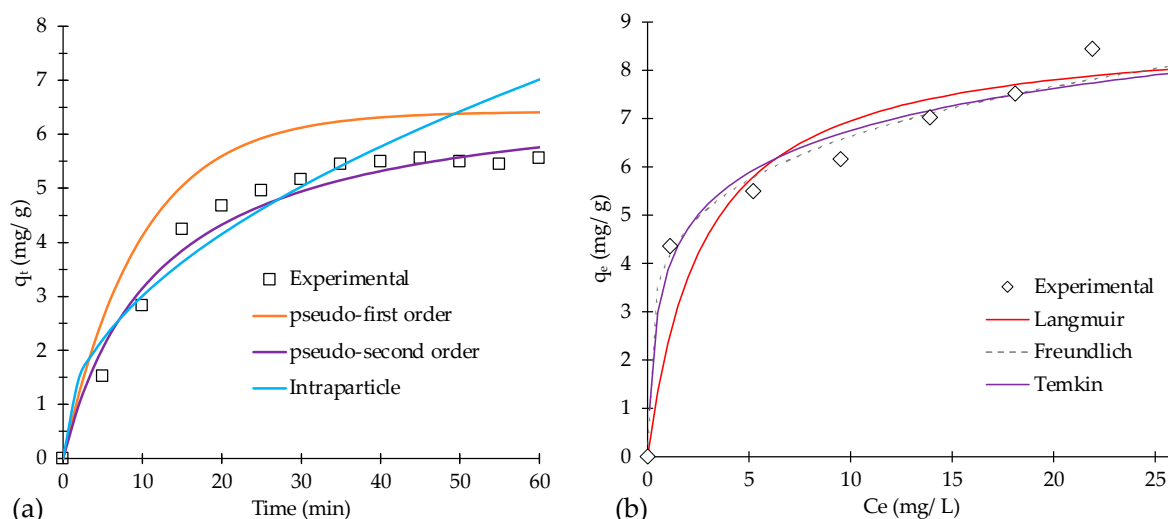


Figure 4. (a) Kinetic fitting of phosphorus adsorption on biochar and (b) isothermal adsorption fitting of phosphorus on biochar.

Table 2. Adsorption fitting results for phosphorus adsorption on biochar.

Model	Parameters ¹		
Pseudo-first-order	q_e (mg g ⁻¹) 6.49	k_1 (min ⁻¹) 0.103	R^2 0.892
Pseudo-second-order	q_e (mg g ⁻¹) 5.51	k_2 (g mg ⁻¹ min ⁻¹) 0.084	R^2 0.977
Intraparticle	C (mg g ⁻¹) 0.244	k_{id} (gmg ⁻¹ min ⁻¹) 0.874	R^2 0.892

Note(s): ¹ data obtained from plots in Figure 4a.

Figure 4b shows the experimental data for the phosphorus adsorption isotherm on cyanobacteria. The curve exhibits an asymptotic shape, indicating that at higher phosphate concentrations, the active sites on the cyanobacteria surface begin to saturate, reaching a point close to equilibrium. This behavior is characteristic of typical adsorption models [48].

Adsorption isotherm models allow the examination of cyanobacteria and phosphate ion interactions. In this study, three adsorption isotherms models were used: (i) Langmuir, (ii) Freundlich, and (iii) Temkin. Table 2 summarizes the modeling results based on these three adsorption isotherms. According to Figure 4b and Table 3, the Langmuir model best describes the phosphate adsorption process on cyanobacteria, as indicated by the highest regression coefficient. This suggests that the adsorption process follows a monolayer mechanism on the cyanobacteria surface.

Table 3. Isothermal adsorption fitting results for phosphorus on biochar.

Model	Parameters ¹		
Langmuir	q_{max} (mg g ⁻¹) 8.89	K_L (L mg ⁻¹) 0.360	R^2 0.973
Freundlich	K_F (mg g ⁻¹) (L mg ⁻¹) ^{1/n} 4.09	$1/n$ 0.209	R^2 0.949
Temkin	B_t (L mg ⁻¹) 3.86	K_T (L g ⁻¹) 21.63	R^2 0.895

Note(s): ¹ data obtained from plots in Figure 4b.

This finding is consistent with previous studies on phosphate adsorption using modified biochar. Xu et al. reported that the Langmuir model effectively described the phosphate adsorption process on Lanthanum-modified biocarbon [49]. However, other authors have found the Freundlich isotherm to be the best-fitting model (see Table 4), indicating that during the adsorption process, it is possible that more than one state occurs during pollutant anchoring. The real mechanism of phosphate adsorption on cyanobacteria-based biochar may involve different processes, including ligand exchange, outer-sphere complexation, electrostatic interaction, surface precipitation, ion exchange, and pore precipitation [50,51].

Comparing the q_e values, the results obtained in this study are comparable to other previously reported maximum adsorption capacities for phosphorus removal using different types of biochar (see Table 4). This finding is significant because the proposed strategy addresses two problems at the same time. Cyanobacterial biomass, which results from excessive phosphorus levels in swamp water, was used to produce biochar for removing phosphorus from the same polluted water source. Additionally, biochar derived from cyanobacteria offers two key benefits: it helps reduce the bioaccumulation process in the swamp and provides a sustainable option for carbon storage [52,53].

Table 4. Maximum adsorption capacity for phosphorus removal using different biochars.

Biochar Source	Maximum Adsorption Capacity (mg g ⁻¹) ¹	Kinetic Model ¹	Isotherm Model ¹	Ref.
Peanut shell	3.01	PSS	Langmuir	[47]
Marine macroalgae	5.22	PSS	Freundlich	[54]
Fe ₂ O ₃ /Bamboo	3.08	Intraparticle	Langmuir	[55]
Sewage sludge	0.7–1.2	Not reported	Not reported	[24]
Pine sawdust	2.0	Not reported	Not reported	[35]
Pineapple	3.70	PSS	Langmuir	[56]
Cyanobacteria	5.51	PSS	Langmuir	This work

Note(s): ¹ data obtained from reports in the literature.

4. Conclusions

In this study, phosphorus was removed from an aqueous solution using biochar produced from cyanobacteria as a carbon source. The kinetic data were best described by the pseudo-second-order model, indicating that the adsorption process is primarily governed by chemisorption. The biochar achieved a maximum adsorption capacity of approximately 5.51 mg PO₄³⁻ g⁻¹. These findings demonstrate that biochar derived from cyanobacterial biomass is a promising and sustainable material for phosphorus removal from water. This approach not only provides an efficient solution for water decontamination but also offers an environmentally friendly strategy for recycling cyanobacterial biomass, contributing to the reduction of nutrient pollution and promoting carbon sequestration.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w17091287/s1>, Figure S1: Growing procedure for increasing biomass of cyanobacteria; Figure S2: Picture of dry biomass from cyanobacteria. Figure S3: Picture of cyanobacteria-biochar obtained after heating T = 350 °C for 2 h. Figure S4: Hypothetical diagram for Phosphate sorption onto biochar.

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E.M.-V.; funding acquisition, C.D.-U., W.V., K.C., J.E.D. and E.M.-V. All authors have read and agreed to the published version of the manuscript.

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References

1. Salehi, M. Global water shortage and potable water safety; Today's concern and tomorrow's crisis. *Environ. Int.* **2022**, *158*, 106936. [[CrossRef](#)] [[PubMed](#)]
2. World Health Organization. *State of the World's Drinking-Water: Executive Summary*; World Health Organization: Geneva, Switzerland, 2023.
3. Muruganandam, M.; Rajamanickam, S.; Sivarethinamohan, S.; Gaddam, M.K.; Velusamy, P.; Gomathi, R.; Ravindiran, G.; Gurugubelli, T.R.; Muniasamy, S.K. Impact of climate change and anthropogenic activities on aquatic ecosystem—A review. *Environ. Res.* **2023**, *238*, 117233.
4. Ruiz, Y.; Medina, L.; Borusiak, M.; Ramos, N.; Pinto, G.; Valbuena, O. Biodegradation of polyethoxylated nonylphenols. *ISRN Microbiol.* **2013**, *2013*, 284950. [[CrossRef](#)]
5. Matsubae, K.; Yamasue, E.; Inazumi, T.; Webeck, E.; Miki, T.; Nagasaka, T. Innovations in steelmaking technology and hidden phosphorus flows. *Sci. Total Environ.* **2016**, *542*, 1162–1168. [[CrossRef](#)] [[PubMed](#)]
6. Yu, H.; Yang, H.; Shi, E.; Tang, W. Development and Clinical Application of Phosphorus-Containing Drugs. *Med. Drug Discov.* **2020**, *8*, 100063. [[CrossRef](#)]
7. Waheed, M.; Yousaf, M.; Shehzad, A.; Inam-Ur-Raheem, M.; Khan, M.K.I.; Khan, M.R.; Ahmad, N.; Abdullah; Aadil, R.M. Channelling eggshell waste to valuable and utilizable products: A comprehensive review. *Trends Food Sci. Technol.* **2020**, *106*, 78–90. [[CrossRef](#)]
8. Akinawo, S.O. Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. *Environ. Chall.* **2023**, *12*, 100733. [[CrossRef](#)]
9. Zhang, H.; Chen, J.; Haffner, D.G. Plateau Lake Water Quality and Eutrophication: Status and Challenges. *Water* **2023**, *15*, 337. [[CrossRef](#)]
10. Diaz-Urbe, C.; Angulo, B.; Patiño, K.; Hernández, V.; Vallejo, W.; Gallego-Cartagena, E.; Romero Bohórquez, A.R.; Zarate, X.; Schott, E. Cyanobacterial Biomass as a Potential Biosorbent for the Removal of Recalcitrant Dyes from Water. *Water* **2021**, *13*, 3176. [[CrossRef](#)]
11. Almanassra, I.W.; Kochkodan, V.; McKay, G.; Atieh, M.A.; Al-Ansari, T. Review of phosphate removal from water by carbonaceous sorbents. *J. Environ. Manag.* **2021**, *287*, 112245. [[CrossRef](#)]
12. Nan, L.; Zhang, Y.; Liu, M.; Zhu, Y.; Zhao, L. Modification of Biochar and Its Removal Mechanism of Phosphorus. In *Water Resources Management and Water Pollution Control*; Environmental Science and Engineering; Springer: Cham, Switzerland, 2024; pp. 61–70.
13. Moharami, S.; Jalali, M. Effect of TiO₂, Al₂O₃, and Fe₃O₄ nanoparticles on phosphorus removal from aqueous solution. *Environ. Prog. Sustain. Energy* **2014**, *33*, 1209–1219. [[CrossRef](#)]
14. Gao, D.; Ji, H.; Li, R.; Tajammal Munir, M.; Wu, X.; Huang, Y.; Li, B. Advancing sustainable phosphorus removal and recovery with Metal-Organic frameworks (MOFs). *Chem. Eng. J.* **2023**, *475*, 145949. [[CrossRef](#)]
15. Tu, Y.J.; You, C.F.; Chang, C.K.; Chen, M.H. Application of magnetic nano-particles for phosphorus removal/recovery in aqueous solution. *J. Taiwan Inst. Chem. Eng.* **2015**, *46*, 148–154. [[CrossRef](#)]
16. Liu, R.; Chi, L.; Wang, X.; Sui, Y.; Wang, Y.; Arandiyani, H. Review of metal (hydr)oxide and other adsorptive materials for phosphate removal from water. *J. Environ. Chem. Eng.* **2018**, *6*, 5269–5286. [[CrossRef](#)]
17. Bao, T.; Damtie, M.M.; Wang, C.; Chen, Z.; Tao, Q.; Wei, W.; Cho, K.; Yuan, P.; Frost, R.L.; Ni, B.J. Comprehensive review of modified clay minerals for phosphate management and future prospects. *J. Clean. Prod.* **2024**, *447*, 141425. [[CrossRef](#)]
18. Al-Hamamre, Z.; Saidan, M.; Hararah, M.; Rawajfeh, K.; Alkhasawneh, H.E.; Al-Shannag, M. Wastes and biomass materials as sustainable-renewable energy resources for Jordan. *Renew. Sustain. Energy Rev.* **2017**, *67*, 295–314. [[CrossRef](#)]
19. Gopinath, K.P.; Vo, D.V.N.; Gnana Prakash, D.; Adithya Joseph, A.; Viswanathan, S.; Arun, J. Environmental applications of carbon-based materials: A review. *Environ. Chem. Lett.* **2020**, *19*, 557–582. [[CrossRef](#)]

20. Li, R.; Wang, B.; Niu, A.; Cheng, N.; Chen, M.; Zhang, X.; Yu, Z.; Wang, S. Application of biochar immobilized microorganisms for pollutants removal from wastewater: A review. *Sci. Total Environ.* **2022**, *837*, 155563. [\[CrossRef\]](#)
21. Azam, R.; Kothari, R.; Singh, H.M.; Ahmad, S.; Ashokkumar, V.; Tyagi, V.V. Production of algal biomass for its biochemical profile using slaughterhouse wastewater for treatment under axenic conditions. *Bioresour. Technol.* **2020**, *306*, 123116. [\[CrossRef\]](#)
22. Nobaharan, K.; Novair, S.B.; Lajayer, B.A.; Hullebusch, E.D. van Phosphorus Removal from Wastewater: The Potential Use of Biochar and the Key Controlling Factors. *Water* **2021**, *13*, 517. [\[CrossRef\]](#)
23. Chen, B.; Chen, Z.; Lv, S. A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. *Bioresour. Technol.* **2011**, *102*, 716–723. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Melia, P.M.; Busquets, R.; Hooda, P.S.; Cundy, A.B.; Sohi, S.P. Driving forces and barriers in the removal of phosphorus from water using crop residue, wood and sewage sludge derived biochars. *Sci. Total Environ.* **2019**, *675*, 623–631. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Shyam, S.; Arun, J.; Gopinath, K.P.; Ribhu, G.; Ashish, M.; Ajay, S. Biomass as source for hydrochar and biochar production to recover phosphates from wastewater: A review on challenges, commercialization, and future perspectives. *Chemosphere* **2022**, *286*, 131490. [\[CrossRef\]](#)
26. Patiño-Camelo, K.; Diaz-Urbe, C.; Gallego-Cartagena, E.; Vallejo, W.; Martinez, V.; Quiñones, C.; Hurtado, M.; Schott, E. Cyanobacterial biomass pigments as natural sensitizer for TiO₂ Thin Films. *Int. J. Photoenergy* **2019**, *2019*, 7184327. [\[CrossRef\]](#)
27. Standard Methods Committee of the American Public Health Association; American Water Works Association; Water Environment Federation. 4500-p phosphorus. In *Standard Methods for the Examination of Water and Wastewater*; Lipps, W.C., Baxter, T.E., Braun-Howland, E., Eds.; American Public Health Association Press: Washington, DC, USA, 2021.
28. Dijkstra, M.L.; Auer, M.T.; Kuczynski, A.; Lambert, R. Determination of bioavailable phosphorus in water samples using bioassay methods. *MethodsX* **2020**, *7*, 100807. [\[CrossRef\]](#)
29. Wang, J.; Guo, X. Rethinking of the intraparticle diffusion adsorption kinetics model: Interpretation, solving methods and applications. *Chemosphere* **2022**, *309*, 136732. [\[CrossRef\]](#)
30. Behera, A.K.; Shadangi, K.P.; Sarangi, P.K. Efficient removal of Rhodamine B dye using biochar as an adsorbent: Study the performance, kinetics, thermodynamics, adsorption isotherms and its reusability. *Chemosphere* **2024**, *354*, 141702. [\[CrossRef\]](#)
31. Al-Ghouti, M.A.; Da'ana, D.A. Guidelines for the use and interpretation of adsorption isotherm models: A review. *J. Hazard. Mater.* **2020**, *393*, 122383. [\[CrossRef\]](#)
32. Wang, J.; Guo, X. Adsorption isotherm models: Classification, physical meaning, application and solving method. *Chemosphere* **2020**, *258*, 127279. [\[CrossRef\]](#)
33. Naima, A.; Ammar, F.; Abdelkader, O.; Rachid, C.; Lynda, H.; Syafiuddin, A.; Boopathy, R. Development of a novel and efficient biochar produced from pepper stem for effective ibuprofen removal. *Bioresour. Technol.* **2022**, *347*, 126685. [\[CrossRef\]](#)
34. Ghorbani, E.; Nowruzi, B.; Nezhadali, M.; Hekmat, A. Metal removal capability of two cyanobacterial species in autotrophic and mixotrophic mode of nutrition. *BMC Microbiol.* **2022**, *22*, 58. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Lou, K.; Rajapaksha, A.U.; Ok, Y.S.; Chang, S.X. Pyrolysis temperature and steam activation effects on sorption of phosphate on pine sawdust biochars in aqueous solutions. *Chem. Pollut. Bioavailab.* **2016**, *28*, 42–50. [\[CrossRef\]](#)
36. Xia, S.; Liang, S.; Qin, Y.; Chen, W.; Xue, B.; Zhang, B.; Xu, G. Significant Improvement of Adsorption for Phosphate Removal by Lanthanum-Loaded Biochar. *ACS Omega* **2023**, *8*, 24853–24864. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Vikrant, K.; Kim, K.H.; Ok, Y.S.; Tsang, D.C.W.; Tsang, Y.F.; Giri, B.S.; Singh, R.S. Engineered/designer biochar for the removal of phosphate in water and wastewater. *Sci. Total Environ.* **2018**, *616–617*, 1242–1260. [\[CrossRef\]](#)
38. Gao, Y.; Chen, N.; Hu, W.; Feng, C.; Zhang, B.; Ning, Q.; Xu, B. Phosphate removal from aqueous solution by an effective clay composite material. *J. Solution Chem.* **2013**, *42*, 691–704. [\[CrossRef\]](#)
39. Han, R.; Han, P.; Cai, Z.; Zhao, Z.; Tang, M. Kinetics and isotherms of Neutral Red adsorption on peanut husk. *J. Environ. Sci.* **2008**, *20*, 1035–1041. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Kumar, P.; Sudha, S.; Chand, S.; Srivastava, V.C. Phosphate Removal from Aqueous Solution Using Coir-Pith Activated Carbon. *Sep. Sci. Technol.* **2010**, *45*, 1463–1470. [\[CrossRef\]](#)
41. Hu, Y.; Guo, T.; Ye, X.; Li, Q.; Guo, M.; Liu, H.; Wu, Z. Dye adsorption by resins: Effect of ionic strength on hydrophobic and electrostatic interactions. *Chem. Eng. J.* **2013**, *228*, 392–397. [\[CrossRef\]](#)
42. Mukherjee, A.; Zimmerman, A.R.; Harris, W. Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma* **2011**, *163*, 247–255. [\[CrossRef\]](#)
43. Lim, S.; Kim, J.H.; Park, H.; Kwak, C.; Yang, J.; Kim, J.; Ryu, S.Y.; Lee, J. Role of electrostatic interactions in the adsorption of dye molecules by Ti₃C₂-MXenes. *RSC Adv.* **2021**, *11*, 6201–6211. [\[CrossRef\]](#)
44. Hu, X.; Zhang, X.; Ngo, H.H.; Guo, W.; Wen, H.; Li, C.; Zhang, Y.; Ma, C. Comparison study on the ammonium adsorption of the biochars derived from different kinds of fruit peel. *Sci. Total Environ.* **2020**, *707*, 135544. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Wu, Q.; Xian, Y.; He, Z.; Zhang, Q.; Wu, J.; Yang, G.; Zhang, X.; Qi, H.; Ma, J.; Xiao, Y.; et al. Adsorption characteristics of pb(ii) using biochar derived from spent mushroom substrate. *Sci. Rep.* **2019**, *9*, 15999. [\[CrossRef\]](#)

46. Sewu, D.D.; Boakye, P.; Woo, S.H. Highly efficient adsorption of cationic dye by biochar produced with Korean cabbage waste. *Bioresour. Technol.* **2017**, *224*, 206–213. [[CrossRef](#)]
47. Jung, K.W.; Hwang, M.J.; Ahn, K.H.; Ok, Y.S. Kinetic study on phosphate removal from aqueous solution by biochar derived from peanut shell as renewable adsorptive media. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 3363–3372. [[CrossRef](#)]
48. Ambaye, T.G.; Vaccari, M.; van Hullebusch, E.D.; Amrane, A.; Rtimi, S. Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. *Int. J. Environ. Sci. Technol.* **2020**, *18*, 3273–3294. [[CrossRef](#)]
49. Xu, Q.; Chen, Z.; Wu, Z.; Xu, F.; Yang, D.; He, Q.; Li, G.; Chen, Y. Novel lanthanum doped biochars derived from lignocellulosic wastes for efficient phosphate removal and regeneration. *Bioresour. Technol.* **2019**, *289*, 121600. [[CrossRef](#)]
50. Zhou, L.; Xu, D.; Li, Y.; Pan, Q.; Wang, J.; Xue, L.; Howard, A. Phosphorus and Nitrogen Adsorption Capacities of Biochars Derived from Feedstocks at Different Pyrolysis Temperatures. *Water* **2019**, *11*, 1559. [[CrossRef](#)]
51. Diaz-Urbe, C.; Ortiz, J.; Duran, F.; Vallejo, W.; Fals, J. Methyl Orange Adsorption on Biochar Obtained from *Prosopis juliflora* Waste: Thermodynamic and Kinetic Study. *ChemEngineering* **2023**, *7*, 114. [[CrossRef](#)]
52. He, D.; Ma, H.; Hu, D.; Wang, X.; Dong, Z.; Zhu, B. Biochar for sustainable agriculture: Improved soil carbon storage and reduced emissions on cropland. *J. Environ. Manag.* **2024**, *371*, 123147. [[CrossRef](#)]
53. Chen, Y.; Van Zwieten, L.; Xiao, K.; Liang, C.; Ren, J.; Zhang, A.; Li, Y.; Dong, H.; Sun, K. Biochar as a green solution to drive the soil carbon pump. *Carbon Res.* **2024**, *3*, 44. [[CrossRef](#)]
54. Zhang, H.; Chen, C.; Gray, E.M.; Boyd, S.E.; Yang, H.; Zhang, D. Roles of biochar in improving phosphorus availability in soils: A phosphate adsorbent and a source of available phosphorus. *Geoderma* **2016**, *276*, 1–6. [[CrossRef](#)]
55. Zhu, Z.; Huang, C.P.; Zhu, Y.; Wei, W.; Qin, H. A hierarchical porous adsorbent of nano- α -Fe₂O₃/Fe₃O₄ on bamboo biochar (HPA-Fe/C-B) for the removal of phosphate from water. *J. Water Process Eng.* **2018**, *25*, 96–104. [[CrossRef](#)]
56. Liao, T.; Li, T.; Su, X.; Yu, X.; Song, H.; Zhu, Y.; Zhang, Y. La(OH)₃-modified magnetic pineapple biochar as novel adsorbents for efficient phosphate removal. *Bioresour. Technol.* **2018**, *263*, 207–213. [[CrossRef](#)] [[PubMed](#)]

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