JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(6), 62–75
https://doi.org/10.12911/22998993/201996
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.02.11
Accepted: 2025.04.05
Published: 2025.04.15

Adsorption kinetics and isotherm study of ammonium and phosphate removal using magnesium-activated biochar

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ABSTRACT

Water eutrophication caused by excessive ammonium (NH_4^+-N) and phosphate (PO_4^{3-}) discharge from wastewater poses severe environmental and public health risks. This study investigates the adsorption performance of magnesium-activated biochar (Mg-biochar) synthesized from locally sourced waste materials – temple waste, coconut husks, and wood – for simultaneous ammonium and phosphate recovery from wastewater. The biochar was produced via pyrolysis at 500 °C and subsequently activated with magnesium chloride ($MgCl_2$) to enhance adsorption efficiency. Batch experiments were conducted using synthetic wastewater containing ammonium and phosphate (50–300 mg/L), evaluating the effects of contact time, biochar dosage, and pH on adsorption performance. The results showed that Mg-biochar achieved a maximum ammonium adsorption capacity of 24.39 mg/g and a phosphate adsorption capacity of 5.57 mg/g, with ammonium removal reaching 80% within the first 30 minutes of contact. Adsorption kinetics followed a second-order model (R^2 = 0.9999 for ammonium and 0.986 for phosphate), indicating chemisorption as the dominant mechanism. Isotherm analysis revealed that adsorption was best described by the Freundlich model, suggesting heterogeneous adsorption behaviour. This study highlights the potential of Mg-biochar as a cost-effective, sustainable solution for nutrient recovery in wastewater treatment, aligning with circular economy principles by converting organic waste into high-value adsorbents. The findings contribute to the development of low-cost, scalable, and efficient biochar-based technologies for mitigating nutrient pollution and improving wastewater management.

Keywords: adsorption, biochar, nutrient, magnesium-activated, wastewater.

INTRODUCTION

Eutrophication in water bodies is caused by the overabundance of nutrients, including ammonium (NH4+-N) and phosphate (P), and poses a significant global challenge to aquatic ecosystems and human health (Kaown et al., 2023; Yates et al., 2022). These nutrients are vital for agricultural productivity, considerably contribute to algae blooms and oxygen depletion in aquatic environments, consequently upsetting ecological equilibrium. The efficient extraction and reclamation of ammonium and phosphate from wastewater are essential for alleviating eutrophication and meeting the increasing need for sustainable nutrient management in agriculture (Howarth and Marino, 2006; Proskynitopoulou et al., 2024; Wu and Vaneeckhaute, 2022). Conventional technologies for nutrient recovery, such as precipitation (Achilleos et al., 2022; Koulouri et al., 2024), crystallization (Fitrika, 2001), ion exchange (Pinelli et al., 2022), and adsorption (Jagadeesh and Sundaram, 2023; Muscarella et al., 2021). Ilori et al. (2023) have demonstrated differing levels of efficacy. Among these, adsorption has proven to be an exceptionally effective technique owing to its simplicity, elevated recovery efficiency, and the possibility of adsorbent regeneration (Alsulaili et al., 2023; Torres Castillo et al., 2021). In recent years, substantial progress in adsorption technology has occurred, featuring the emergence of innovative adsorbents such as biochar (Chew et al., 2022; Goldschmidt and Buffam, 2023), mesoporous materials (Dey and Mavi, 2022; Susilawati

et al., 2023), and hybrid nanocomposites (Ribeiro et al., 2017), which exhibit improved nutrient recovery efficacy. Conventional techniques frequently encounter obstacles, including elevated operational costs, restricted scalability, and inefficiencies in the treatment of highly concentrated effluent. For example, sophisticated adsorbents such as Fe-MoS_4-layered double metals (Li et al., 2021) and modified zeolites (Markou et al., 2014; Zhang et al., 2017) have superior performance but frequently present cost limitations for large-scale utilization.

Biochar, a carbon-dense substance generated from the pyrolysis of biomass, has garnered interest as a sustainable and economical option for nutrient recovery. Its porous architecture and elevated surface area facilitate efficient adsorption of ammonium and phosphate ions, while its derivation from waste biomass adheres to circular economy principles by minimizing landfill waste and enhancing resource valorization (Barbhuiya et al., 2024; Shi et al., 2023; Yang et al., 2018). Recent advancements indicate that magnesium activation might augment the adsorption capacity of biochar by creating more binding sites for nutritional ions, hence enhancing its efficacy and environmental compatibility (Bolan et al., 2023; Erdem, 2021).

This research examines the creation and assessment of magnesium-activated biochar produced from a distinctive amalgamation of locally sourced waste materials, including temple debris, coconut husks, and wood. These feedstocks are plentiful and inadequately exploited, offering a sustainable potential for waste-to-resource transformation. This research examines the concurrent recovery of ammonium and phosphate, filling a significant gap in the literature, unlike prior studies that focused solely on the adsorption of these nutrients individually (Ha et al., 2023; Wijaya et al., 2023; Wijaya et al., 2023). This study offers novel insights into the mechanisms of dual-nutrient recovery by the analysis of adsorption kinetics, isotherms, and capacities (Hofmann et al., 2024; Panasiuk, 2012; Silva et al., 2023).

The imperative of phosphorus recovery is highlighted by its limited supply and increasing agricultural demand (Riseh et al., 2024; Singh et al., 2022). The traditional dependence on mined phosphate rock is unsustainable due to decreasing reserves and escalating price volatility. Likewise, nitrogen loss from agricultural runoff intensifies environmental and economic inefficiencies (Lavallais and Dunn, 2023). This study integrates nitrogen recovery into wastewater treatment, addressing water pollution while providing a sustainable method for creating nutrient-enriched biochar as an alternative fertilizer. These advances are expected to diminish reliance on non-renewable resources and improve agricultural output (Chew et al., 2022; Marcińczyk et al., 2022; Rai et al., 2014). This research is consistent with global sustainability goals, encompassing waste minimization, resource reclamation, and the advancement of eco-friendly techniques. The aim of this study is also to investigate the effectiveness of magnesium-activated biochar in removing ammonium (NH_4^+-N) and phosphate (PO_4^{3-}) ions from synthetic wastewater.

METHOD

Preparation of magnesium-activated biochar

Biochar was generated from refuse-derived fuel (RDF) consisting of temple debris, coconut husks, and wood. The feedstocks were purified, desiccated, and milled to a consistent particle size. RDF briquettes underwent pyrolysis in a muffle furnace at 500 °C for 2 hours under oxygen-restricted conditions to achieve complete carbonization. The charcoal was subsequently activated with a 200 mg/L magnesium chloride ($MgCl_2$) solution at pH 7. The saturated biochar was agitated for 12 hours at ambient temperature to promote magnesium integration. The biochar was filtered, rinsed with deionized water to eliminate residual magnesium chloride, and dried at 105 °C for 12 hours until a consistent weight was attained. The magnesium-activated biochar was stored in sealed containers until needed.

Batch adsorption experiments

Synthetic wastewater was produced with ammonium (NH_4^+) and phosphate (PO_4^{3-}) ions at initial concentrations of 200 mg/L each, utilizing ammonium chloride (NH_4Cl) and potassium phosphate (KH_2PO_4). The pH was calibrated to 7.0 utilizing 0.1 M hydrochloric acid (HCl) or sodium hydroxide (NaOH). In each experiment, 250 mL of synthetic wastewater was deposited in 500 mL Erlenmeyer flasks containing 0.1, 0.5, 0.75, or 1.5 grams of magnesium-activated biochar. The flasks were

stirred on an orbital shaker at 80 rpm and kept at 25 °C. Samples were obtained at 0, 15, 20, 60, and 90 minutes, filtered through 0.45 µm membrane filters, and analyzed to ascertain ammonium and phosphate contents. After the adsorption period, the biochar was separated by filtration, and the amounts of ammonium and phosphate in the solution were assessed according to conventional analytical methods by utilizing UV-Vis spectrophotometry.

Analytical techniques

The adsorption rate denotes the velocity at which the adsorbate (ammonium or phosphate) adheres to the charcoal. The kinetics of ammonium and phosphate adsorption were analysed using first order and second-order kinetic models. The first-order kinetic model posits that the adsorption rate is directly proportional to the temporal variation in adsorbate concentration, represented by the following equation:

$$ln(C_0 - C_t) = ln(C_0) - k_1 \times t \quad (1)$$

where: C_0 is the initial concentration of the adsorbate (mg/L), C_t is the concentration at time tt (mg/L), k_1 is the rate constant for the first-order reaction (min^{-1}), t_t is the time (minutes).

The second-order kinetic model was employed to characterize the adsorption process, wherein the adsorption rate is proportional to the square of the adsorbate concentration (Nafi'ah, 2016; Nurhidayati et al., 2022). The equation is provided above in the adsorption rate section. The second-order model is more appropriate when adsorption is governed by chemisorption. The optimal model for ammonium and phosphate adsorption was determined by comparing the R^2 values of both models (Agusriyadin, 2020; Gonçalves et al., 2022). The adsorption rate constant (k) was determined utilizing the second-order kinetic model. The fundamental equation for second-order kinetics is expressed as:

$$\frac{1}{(q_t - q_e)} = \frac{1}{k} \times t + \frac{1}{q_e} \quad (2)$$

where: q_t is the amount of adsorbate adsorbed at time tt (mg/g), q_e is the adsorption capacity at equilibrium (mg/g), k is the rate constant (mg/g·min), t is the time of adsorption (minutes).

Isotherm models were employed to assess the adsorption equilibrium and ascertain the adsorption capacity of biochar for both ammonium and phosphate. Two prevalent models were utilized: Langmuir and Freundlich. The Langmuir model posits monolayer adsorption on a surface with a limited number of adsorption sites. The formula is:

$$\frac{1}{q_e} = \frac{1}{Q_m \times K_L} \times \frac{1}{C_e} + \frac{1}{Q_m} \quad (3)$$

where: q_e is the adsorption capacity (mg/g) at equilibrium, C_e is the equilibrium concentration of the adsorbate (mg/L), Q_m is the maximum adsorption capacity (mg/g), K_L is the Langmuir constant related to the adsorption energy (L/mg).

The Freundlich model describes heterogeneous adsorption with varying adsorption energies. The equation is:

$$q_e = K_f \times C_e^{\frac{1}{n}} \quad (4)$$

where: q_e is the adsorption capacity (mg/g) at equilibrium, C_e is the equilibrium concentration of the adsorbate (mg/L), K_f is the Freundlich constant, representing the adsorption capacity (mg/g), n is the Freundlich constant, representing the adsorption intensity.

The results from the adsorption studies were analyzed using both models to assess the adsorption capacity and intensity for ammonium and phosphate. The model that best matched the experimental data was selected for additional investigation. The experimental data for ammonium and phosphate adsorption were examined by regression techniques to determine the rate constants (k) and the equilibrium adsorption capacities. The R^2 values from the Langmuir and Freundlich isotherms, along with the first-order and second-order kinetic models, were employed to evaluate the goodness of fit (Ilori et al., 2023; Wijayanti and Kurniawati, 2019). The model yielding the highest R^2 value was deemed the most accurate description of the adsorption process for each nutrient. Scanning electron microscopy (SEM) was employed to examine alterations in surface morphology and structure of the biochar prior to and following activation.

RESULT AND DISCUSSION

Ammonium and phosphate adsorption

The adsorption of ammonium and phosphate by biochar is significantly affected by two primary factors: reaction time and the quantity of biochar incorporated into the sample. The plots illustrate the dynamics of concentration variations for ammonium and phosphate under different reaction times and biochar dosages.

Effect of reaction time on adsorption

The initial graph (Figure 1) illustrates the temporal variations in the concentrations of ammonium and phosphate from 0 to 90 minutes. At the outset, concentrations of ammonium and phosphate are elevated; nevertheless, a substantial decrease transpires within the initial 20 minutes of the reaction. This swift decline is due to biochar's adsorption capacity being most effective at the onset of the process. The concentration of ammonium decreases markedly within the initial 20 minutes, stabilizing at approximately 160 mg/L thereafter. Conversely, phosphate diminishes more gradually and stabilizes at approximately 160 mg/L after the initial 20 minutes, signifying a slower adsorption process in comparison to ammonium. The swift initial adsorption of ammonium indicates that biochar possesses a strong initial affinity for ammonium ions, which are typically smaller and more readily adsorbed owing to their charge and ionic characteristics (Muscarella et al., 2021; Zeng et al., 2013). The ammonium ion, being a lower ionic radius, is frequently seen as more readily adsorbed onto biochar surfaces owing to its capacity to establish robust electrostatic contacts. Conversely, phosphate ions are bigger and generally establish weaker interactions with biochar, which may elucidate the slower adsorption process noted for phosphate (Zhang et al., 2020).

The occurrence of fast initial adsorption succeeded by gradual stability in ammonium and phosphate concentrations is a prevalent characteristic in adsorption kinetics. A comparable observation indicated that biochar exhibited fast adsorption in the initial contact stages, followed by a gradual absorption over time (Awogbemi and Kallon, 2023; Piash et al., 2021). The adsorption process typically adheres to a first-order kinetic model for both ammonium and phosphate, characterized by an initially high rate of adsorption that diminishes as the biochar surface adsorption sites reach saturation.

Effect of biochar dosage on adsorption

Figure 2 depicts the influence of biochar dose (from 0 to 1.5 grams) on the final concentrations of ammonium and phosphate after a duration of 90 minutes. As the biochar mass escalates, the concentrations of ammonium and phosphate diminish, with the most pronounced decline noted at the maximum biochar dose of 1.5 grams. This suggests that the adsorption capacity of biochar is directly related to its mass, as a greater quantity of biochar offers increased surface area and adsorption sites for pollutants.

At the minimum biochar dosage (0 grams), the levels of both ammonium and phosphate remain virtually constant, indicating that in the absence of biochar, no adsorption takes place. With the introduction of biochar (0.1–1.5 grams), concentrations of ammonium and phosphate consistently diminish. At the maximum dosage (1.5 grams), the concentration of ammonium is minimized, indicating nearly full adsorption of ammonium ions. Phosphate exhibits a comparable trend; however, the reduction is less significant

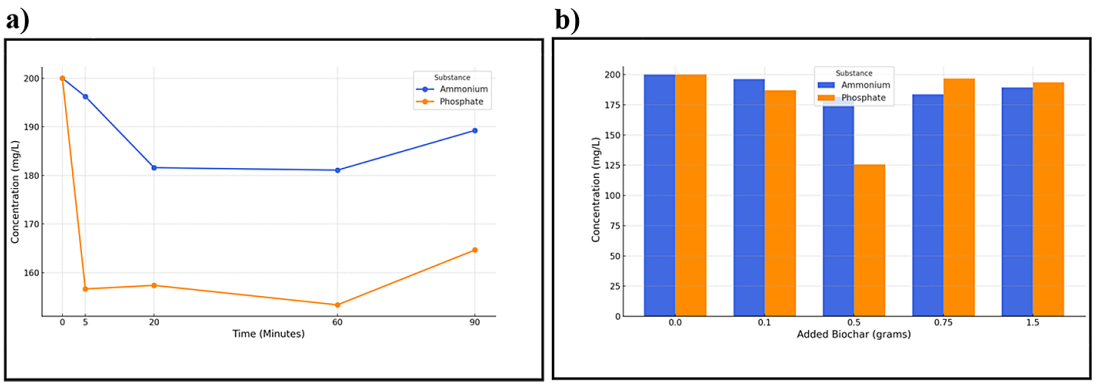

Figure 1. The nutrient concentration during the adsorption according to contacted time (a) and added biochar (b)

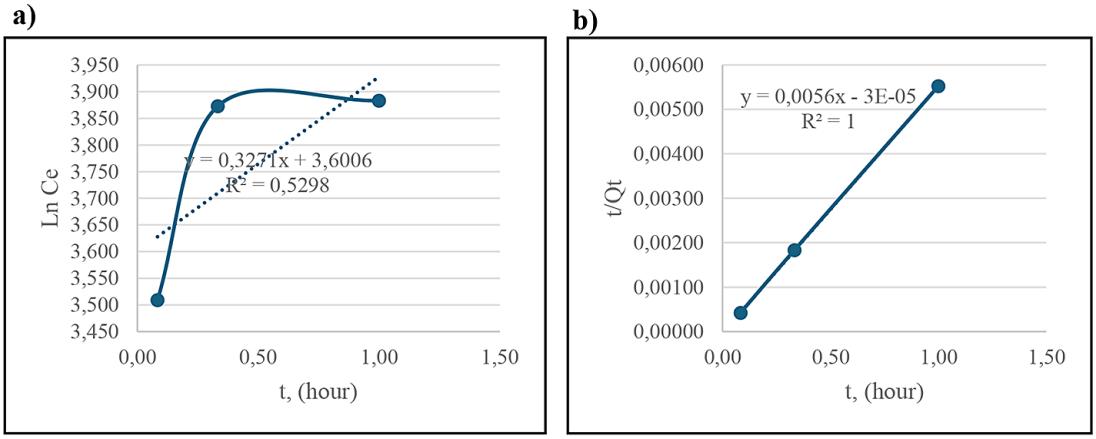

Figure 2. Kinetic reaction first order (a) and second order (b) for ammonium adsorption

than that of ammonium, suggesting that biochar possesses a marginally lesser capacity for phosphate adsorption under identical conditions.

The enhanced adsorption effectiveness with elevated biochar dosages is due to the greater availability of adsorption sites. The porous architecture of biochar, characterized by its extensive surface area and diverse functional groups, is essential for the adsorption of pollutants (Gai et al., 2014; Parthasarathy et al., 2023; Olugbenga et al., 2024). Increased biochar addition enhances the accessible surface area for ammonium and phosphate ions, hence augmenting total adsorption effectiveness. Comparable patterns have been noted in further investigations examining the elimination of ammonium and phosphate from aqueous solutions utilizing biochar. A notable enhancement in ammonium and phosphate removal with elevated biochar doses was observed, attributed to the increased surface area facilitating ion exchange and adsorption (Gong et al., 2017).

1. The analysis of ammonium and phosphate adsorption demonstrates significant disparities in the interaction of biochar with these two pollutants. Both ions demonstrate a reduction in concentration with time and with increased charcoal mass; however, ammonium is absorbed more rapidly and efficiently than phosphate. This may be attributable to various factors:
2. Ionic dimensions and valence: Ammonium ions (NH_4^+) possess a reduced ionic radius and exhibit a more potent electrostatic attraction to the negatively charged functional groups present on biochar. This facilitates a swifter and more efficient adsorption process. Conversely, phosphate ions (PO_4^{3-}) are bigger and possess a distinct charge distribution, which engenders diminished interactions with the biochar surface, culminating in reduced adsorption rates (Dey and Mavi, 2022; Dias et al., 2010; Konneh et al., 2021).
3. Surface chemistry of biochar: The surface chemistry of biochar, particularly the presence of oxygen-containing functional groups (including carboxyl, phenolic, and lactone groups), profoundly affects the adsorption of ammonium and phosphate. These functional groups are predisposed to establish stable interactions with ammonium, hence promoting its accelerated adsorption (Osadebe et al., 2024; Xu et al., 2018). Larger phosphate ions with distinct ionic characteristics tend to establish weaker interactions with the charcoal surface.
4. Mechanisms of adsorption: Ammonium is predominantly adsorbed by electrostatic interactions and ion exchange, whereas phosphate ions are more inclined to establish surface compounds with charcoal through chemical bonding or precipitation. The disparity in adsorption methods results in a more swift and effective elimination of ammonium relative to phosphate (Ahmad et al., 2024; Dong et al., 2024).

This study indicates that biochar exhibits superior ammonium adsorption compared to phosphate, primarily attributable to the smaller ionic radius and enhanced electrostatic interactions between ammonium and the surface functional groups of biochar (Gotore et al., 2022; Koulouri et al., 2024; Syukur et al., 2023). It is noted that augmenting biochar dosage improves the removal of ammonium and phosphate, corroborating the study's findings that elevated biochar doses result in enhanced adsorption (Hofmann et al., 2024). Moreover, research indicates that the surface

characteristics of biochar—specifically surface area, pore volume, and functional group composition—substantially affect its adsorption efficacy. Biochar produced from diverse feedstocks and subjected to distinct circumstances demonstrates differing adsorption capabilities for ammonium and phosphate. Biochar produced from agricultural residues typically exhibits elevated surface areas and enhanced cation exchange capabilities, hence augmenting its adsorption efficacy (Rahim et al., 2024; Rawat et al., 2023).

The findings of this investigation unequivocally demonstrate that both reaction time and biochar dosage substantially affect the adsorption of ammonium and phosphate. Ammonium is adsorbed more rapidly and efficiently than phosphate, probably owing to its smaller size and enhanced electrostatic contact with the surface of biochar. Augmenting the biochar bulk enhances adsorption for both pollutants, as greater quantities of biochar offer increased surface area for ion interaction. The results align with prior studies that highlight the significance of biochar dose and surface chemistry in enhancing nutrient removal (Finkler et al., 2023; Romero et al., 2021). Biochar offers a viable option for the extraction of nitrogen and phosphorus from wastewater and other polluted aquatic systems, with potential uses in environmental management and pollution reduction.

Kinetic analysis of ammonium and phosphate adsorption

Kinetic study facilitates the comprehension of the adsorption rate and the mechanisms underlying ammonium and phosphate absorption by biochar. The experimental data for ammonium and phosphate adsorption were analyzed using first-order and second-order kinetic models to determine the prevailing mechanism (Figure 3).

Ammonium adsorption kinetics

The adsorption of ammonium in stabilization pond samples exhibits a swift decline in concentration during the initial 30 minutes of contact time, succeeded by a gradual fall until equilibrium is reached after 60 minutes. The experimental data was analyzed using both first-order and second-order kinetic models. The findings demonstrate that second-order kinetics yielded a markedly superior match, evidenced by a high R^2 value ($R^2 = 0.9999$). This indicates that ammonium adsorption is controlled by chemisorption, with the rate-limiting step being the chemical interaction between ammonium ions and the biochar surface. These biochars often display second-order kinetics in ammonium adsorption due to interactions with surface functional groups and ion exchange mechanisms.

Phosphate adsorption kinetics

The phosphate adsorption exhibits an initial decrease in concentration, with the adsorption rate decelerating after the first 30 minutes, similar to ammonium. The second-order model demonstrated a superior fit ($R^2 = 0.986$) relative to the first-order model ($R^2 = 0.75$). This further substantiates that phosphate adsorption on biochar adheres to chemisorption kinetics, although at a reduced rate relative to ammonium. The protracted adsorption of phosphate is due to its greater ionic size and intricate interactions with the biochar surface, necessitating additional time to establish stable bonds (Bolan et al., 2023; Samaraweera et al., 2023). The results highlight that ammonium and phosphate adsorption on biochar is governed by second-order kinetics, with chemisorption being a pivotal factor in the adsorption mechanism. The rapid initial adsorption, succeeded by a slower phase, indicates that both ammonium and phosphate exhibit strong interactions with the biochar

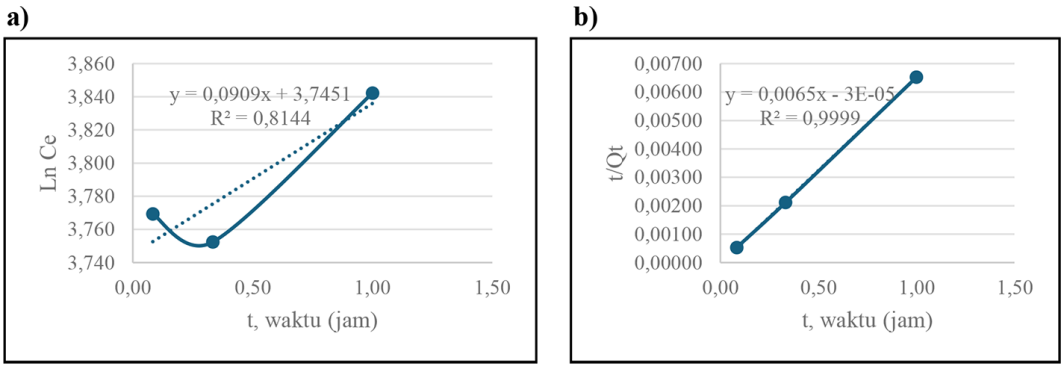

Figure 3. Kinetic reaction first order (a) and second order (b) for phosphate adsorption

surface; nevertheless, phosphate necessitates additional time for complete adsorption owing to its bigger size and distinct chemical properties (Chew et al., 2022; Erdem, 2021).

Isotherm analysis of ammonium and phosphate adsorption

Isotherm models characterize the adsorption equilibrium between the adsorbate (ammonium or phosphate) and the adsorbent (biochar). The stabilizing pond sample data were analyzed using the Langmuir and Freundlich isotherm models to assess adsorption capacity and behavior (Liu et al., 2015; Wijayanti and Kurniawati, 2019). The outcomes of isotherm analysis for ammonium and phosphate adsorption are illustrated in Figures 4 and 5.

Ammonium adsorption isotherm

The ammonium adsorption data aligns most closely with the Freundlich isotherm model (R^2 = 0.9327). This signifies that ammonium is adsorbed onto a heterogeneous biochar surface, indicating the presence of diverse adsorption sites with variable binding energies. The Freundlich constant (Kf) for ammonium is 557.44 mg/g, indicating a modest adsorption capability. The n-value of 0.62, being less than 1, signifies that ammonium adsorption is not particularly advantageous under the conditions employed in this study. This aligns with prior research by Ren (Ren et al., 2023) which indicated analogous findings regarding ammonium adsorption on biochar, suggesting the involvement of numerous adsorption sites, while noting that adsorption effectiveness might be enhanced by modified biochar surface characteristics. The Langmuir model demonstrated limited efficacy in fitting the ammonium adsorption data, as seen by low R^2 values, suggesting that ammonium adsorption on biochar does not conform to monolayer adsorption (Addai et al., 2023; Yang et al., 2018). The observations indicate that ammonium is adsorbed in many layers, reflecting multisite adsorption characteristic of biochar's heterogeneous surface.

Phosphate adsorption isotherm

The phosphate adsorption data align more closely with the Freundlich isotherm model (R^2 = 0.9288), indicating that phosphate adsorption on biochar is affected by many adsorption sites with differing energies. The Freundlich constant

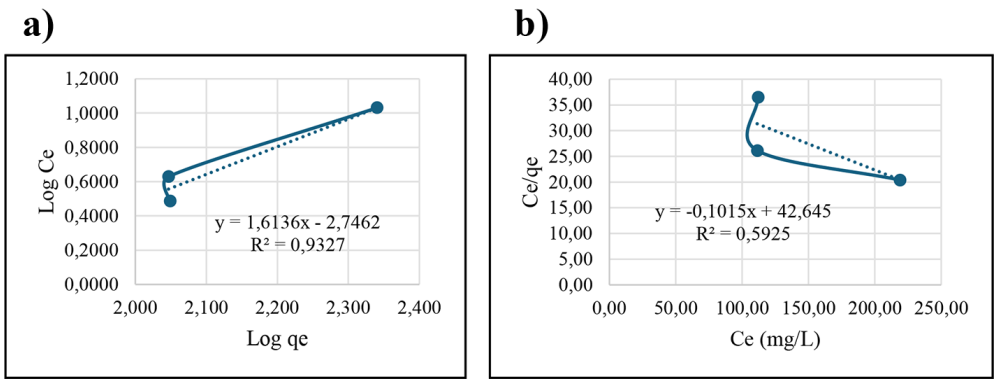

Figure 4. Isotherm analysis for ammonium adsorption: (a) Isotherm Freundlich (b) Isotherm Langmuir

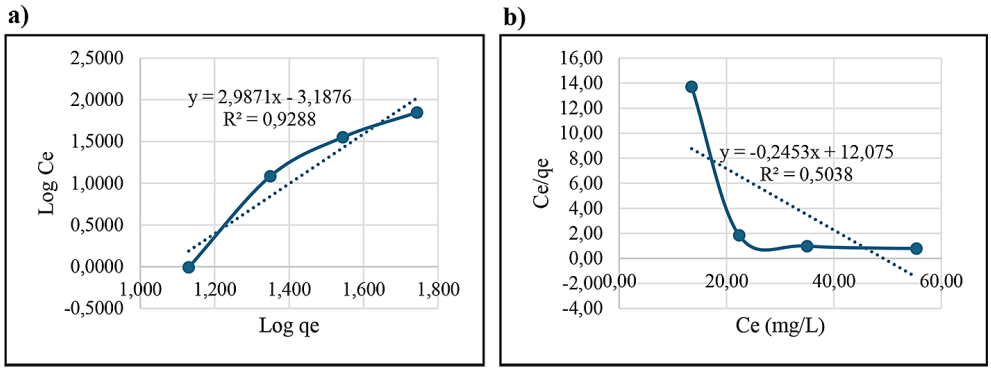

Figure 5. Isotherm analysis for phosphate adsorption: (a) Isotherm Freundlich (b) Isotherm Langmuir

for phosphate adsorption is 1540.28 mg/g, above that of ammonium, indicating a superior overall adsorption capacity for phosphate. Nevertheless, the n-value for phosphate is 0.33, signifying that phosphate adsorption is less favorable than that of ammonium. The adsorption of phosphate on biochar is intricate and less efficient because of the higher ionic size and the necessity for several adsorption sites for successful binding (Gong et al., 2017; Zeng et al., 2013). The Langmuir model inadequately represented the phosphate adsorption data, indicating that phosphate does not conform to monolayer adsorption on biochar but rather experiences multilayer adsorption.

The adsorption behaviors identified in this study align with the findings of other studies. The Freundlich model is often seen to effectively characterize nutrient adsorption, including ammonium and phosphate, on biochar, attributable to the diverse characteristics of biochar surfaces (Gong et al., 2017; Zhang et al., 2020). Moreover, the Freundlich isotherm demonstrated superior fitting compared to the Langmuir model in this work, corroborating the finding that biochar surfaces are heterogeneous, comprising a spectrum of adsorption sites with differing energies.

This study illustrates that biochar serves as an efficient adsorbent for diminishing ammonium and phosphate levels in actual effluent from stabilization ponds. The kinetic analysis indicated that the adsorption of both ammonium and phosphate adheres to second-order kinetics, implying that chemisorption is the predominant mechanism. The Freundlich isotherm model well characterizes the adsorption behavior, indicating that the biochar surface is heterogeneous and can adsorb ammonium and phosphate ions in many layers. The findings suggest that biochar is an effective medium for wastewater treatment, especially in the elimination of nutrients such as ammonium and phosphate (Barbhuiya et al., 2024; Chew et al., 2022). Further optimization of biochar characteristics and enhanced adsorption capacities via surface modification or activation could improve its efficacy for environmental applications, including nutrient recovery and pollution management. The comprehensive value of kinetic and isotherm analysis is displayed in Table 1.

The regeneration of Mg-biochar is essential for its effective use in wastewater treatment, as it improves sustainability and cost-efficiency. Many studies have investigated different regeneration methods to get the adosrbent, such as chemical desorption, thermal reactivation, and biological methods (Jiang et al., 2019; Marcińczyk et al., 2022). Using alkaline or acidic solutions, like NaOH or HCl, to desorb biochar has been shown to effectively release ammonium and phosphate ions, which makes it easier to use biochar again and again (Xu et al., 2018). Thermal regeneration at moderate temperatures (300–500 °C) has shown that biochar can get its pores and surface functional groups back without sustaining a lot of damage to its structure (Bolan et al., 2023).Moreover, biological regeneration through microbial processes has garnered interest as an eco-friendly option, but its efficacy remains inconsistent (Osadebe et al., 2024). Even though these regeneration methods look promising, there are still some problems to solve. Future studies ought to concentrate on refining regeneration conditions, analysing long-term efficacy, and determining the economic viability of extensive uses. Using circular economy ideas in biochar regeneration solutions is important for making them work better in long-term wastewater treatment and nutrient recovery.

Biochar morphology

SEM images offer comprehensive insights into the surface architecture, porosity, and micromorphology of biochar, which are essential determinants affecting its adsorption capacity and efficacy in wastewater treatment (Alsulaili et al., 2023; Susilawati et al., 2023). Figure 6 presents the scanning electron microscopy pictures of inactivated biochar. These photos illustrate a coarse and uneven surface featuring unopened pores and shattered particles. The surface seems to be less

Table 1. The kinetic and isotherm value of ammonium and phosphate adsorption

Analysis	Phosphate	Ammonium
First order kinetic (per hour)	0.09	1.41
Second order kinetic (per gram hour)	1.41	1.04
Isotherm Freundlich (mg/g)	1540.28	557.44
Isotherm Langmuir (mg/g)	-49.22	-420.14

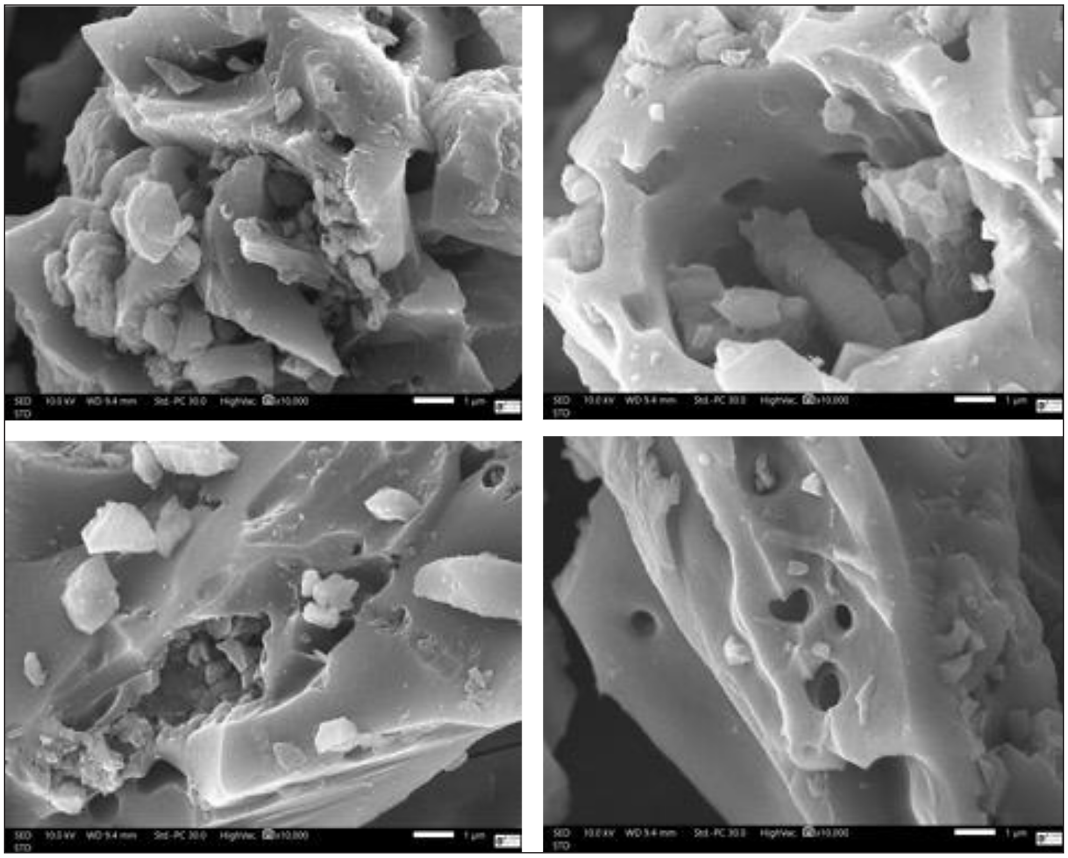

Figure 6. SEM of biochar before activation

porous, exhibiting a comparatively smooth texture comparing to activated biochar. This shape indicates that untreated biochar may possess a reduced surface area, hence constraining the availability of active sites for adsorption. The findings align with those of (Chew (2022) who noted that untreated biochar possesses fewer surface functional groups and a less developed pore structure, consequently diminishing its efficacy in eliminating pollutants like ammonium and phosphate. The absence of microporosity and macro porosity in untreated biochar may render it less effective than activated biochar in nutrient adsorption from wastewater (Abdelghany et al., 2023).

Figure 7 depicts the biochar after to activation with magnesium. The surface exhibits considerable structural alterations, characterized by larger pores, heightened roughness, and more pronounced micropores. The activation process with magnesium has likely increased the surface area and generated more functional groups on the biochar, enhancing its reactivity and capacity to adsorb ammonium and phosphate ions. The enhancement in surface morphology is characteristic of activated biochar, wherein physical or chemical treatments augment its porosity and active sites (Marcińczyk et al., 2022; Phares et al., 2022). The coarser texture and enlarged pores observed in the SEM images correspond to an enhanced adsorption capacity, as these structural modifications offer additional sites for ion exchange and surface complexation with contaminants (Alsulaili et al., 2023; Muscarella et al., 2021).

The SEM examination reveals substantial morphological alterations in biochar when utilized for adsorption in actual wastewater. The activation procedure increases biochar's surface area and porosity, hence enhancing its adsorption ability. The alterations noted in the biochar surface during ammonium and phosphate adsorption, including pore obstruction and the creation of surface complexes, are indicative of efficient nutrient removal and imply that biochar may serve as a feasible medium for wastewater treatment. The adsorption capacity of biochar for ammonium and phosphate is markedly improved post-activation, resulting in an increased number of adsorption sites (Panasiuk, 2012; Rey-Martínez et al., 2024; Xiao et al., 2016).Furthermore, the adsorption sites may reach saturation during actual wastewater treatment,

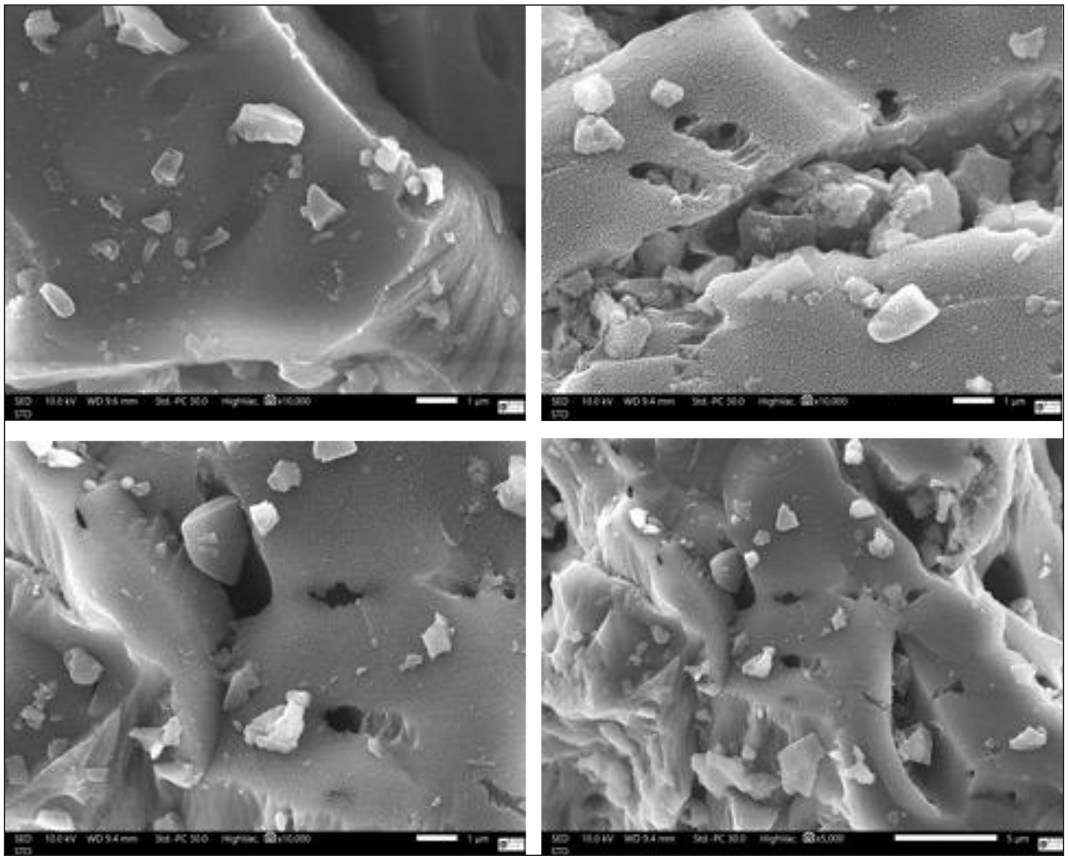

Figure 7. SEM of biochar after activation

leading to alterations in biochar's surface shape, which are crucial for comprehending its adsorption kinetics and capacity.

CONCLUSIONS

This study demonstrates the effectiveness of magnesium-activated biochar for the simultaneous removal of ammonium and phosphate from wastewater. The adsorption performance of biochar was significantly enhanced through magnesium activation, leading to a maximum ammonium adsorption capacity of 24.39 mg/g and phosphate adsorption capacity of 5.57 mg/g. The adsorption process followed second-order kinetics, confirming chemisorption as the primary mechanism, with ammonium removal reaching 80% within the first 30 minutes of contact. Freundlich isotherm modeling suggested heterogeneous adsorption behavior, with multiple binding sites contributing to nutrient uptake. The findings indicate that Mg-biochar presents a viable, cost-effective, and environmentally friendly alternative to conventional wastewater treatment methods, aligning with circular economy principles by repurposing biomass waste into functional adsorbents. This approach not only enhances nutrient recovery efficiency but also provides a sustainable strategy for reducing reliance on chemical fertilizers, contributing to agricultural sustainability. To ensure the sustainability of Mg-biochar in wastewater treatment, future research should focus on optimizing its regeneration process and evaluating its long-term performance under various environmental conditions.

Acknowledgements

The authors would like to thank the Ministry of Education, Culture, Research and Technology of Republic of Indonesia for funding this study under National Applied Research Grant 2024.

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