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Original Research Article

Simultaneous Recovery of Ammonium and Phosphate from Wastewater Using Magnesium-activated Temple Waste Biochar

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ABSTRACT

Nutrient pollution from ammonium and phosphate in wastewater presents serious environmental challenges, including water eutrophication and resource inefficiency. The study aimed to analyse how magnesium-activated biochar made from temple waste could be used as a sustainable material for simultaneously adsorbing nutrients. The biochar was synthesised through pyrolysis and magnesium chloride activation, then applied to real wastewater from stabilisation ponds in Bali. The adsorption dynamics for both ammonium and phosphate were consistent with pseudo-second-order models, suggesting that chemical absorption was the prevailing mechanism. The Freundlich isotherm model provided the best fit, suggesting heterogeneous multilayer adsorption. Results demonstrated that adsorption capacity and rate varied across different wastewater sources, with the highest adsorption rates corresponding to ponds exhibiting more favourable surface interactions. Significantly, the adsorption rate constant for phosphate surpassed that of ammonium in some cases, emphasising the influence of ionic properties and biochar surface heterogeneity. The results confirm that biochar made from waste can effectively recover nutrients and should be included in circular approaches for managing wastewater.

KEYWORDS

Adsorption, Biochar, Nutrient recovery, Magnesium-activated biochar, Wastewater, Ammonium, Phosphate, Circular economy.

INTRODUCTION

Elevated levels of nutrients, such as phosphorus (P) compounds and ammonium (NH_4^+-N), are contributing to water eutrophication, a critical worldwide concern affecting both aquatic environments [1] and human well-being [2]. These essential nutrients play a crucial role in agricultural output, making a significant contribution to the growth of algae and the reduction of oxygen levels in bodies of water, ultimately disrupting the natural balance of the environment [3]. Effective removal and recovery of ammonium and phosphate from wastewater are critical [4] not only for mitigating eutrophication but also for addressing the

growing demand for sustainable nutrient management in agriculture [5]. Achilleos *et al.* [6] investigated struvite precipitation as a method for nutrient recovery from wastewater, Koulouri *et al*. [7] discovered that nitrogen and phosphorus can be enriched in biochar through a process of adsorption and precipitation, and Dewi & Masduqi [8] demonstrated the effectiveness of the crystallisation process using silica sand media for removing phosphate. Pinelli *et al.* [9] focused on developing an ion exchange process for recovering ammonium from wastewater, and Muscarella *et al.* [10] demonstrated the efficacy of ammonium adsorption using modified zeolite.

Adsorption is currently viewed as a highly effective processing method [11], primarily due to its simplicity [12], as well as its ability to recover nutrients efficiently [13] and the potential for regenerating the adsorbent [14]. Goldschmidt & Buffam [15] reported that the addition of biochar can increase nutrient retention in the environmental system, while Susilawati *et al.* [16] devised a zeolite and activated charcoal-based filter material from cocoa waste that effectively absorbs ammonia. Ribeiro *et al.* [17] researched hybrid magnetic nanocomposites that can enhance nutrient recovery in wastewater. However, these conventional approaches often face challenges such as high operational costs, limited scalability, and inefficiencies in treating highly concentrated wastewater [18]. Further, Li *et al.* [19] demonstrated that iron-modified biochar exhibits superior performance in nitrogen and phosphorus recovery. Zhang *et al.* [20] optimised the regeneration of zeolite and reported an increase in nitrogen removal efficiency. Markou *et al.* [21] emphasised that the use of natural zeolite can serve as a sustainable alternative, although the cost remains high on a large scale.

Biochar is a carbon-rich material produced by processing organic matter in low-oxygen combustion conditions. It is an alternative for an affordable and eco-friendly solution for adsorbent materials to recover nutrients from wastewater for agricultural use. Its extensive specific surface area and porous composition make it ideal for effectively adsorbing ammonium and phosphate ions. Barbhuiya *et al.* [22] affirmed that the use of biochar aligns with the principles of the circular economy. Shi *et al.* [23] explored the inorganic compound content in biochar that could be reutilised. Yang *et al.* [24] reported that utilising biomass waste as biochar enhances resource value and reduces waste disposal to landfills. Meanwhile, Erdem [25] discovered that activation with magnesium enhances the surface reactivity of biochar, creating more binding sites for nutrient ions. Furthermore, Bolan *et al.* [26] stated that magnesium-activated biochar can improve soil health and microbial balance, thereby making it a more environmentally friendly option. This evidence illuminates that magnesium activation is an effective strategy for enhancing adsorption efficiency and environmental sustainability.

The present study focuses on combining temple waste, coconut husks, and wood in a digestion process, along with the development and evaluation of a biochar enriched with magnesium produced from these materials. There is a significant amount of biodegradable materials that can be used as inputs for the process. Yet, they are not fully utilised, offering a sustainable alternative for converting waste into resources. Unlike previous studies that primarily investigated the adsorption of either ammonium or phosphate individually [27], current research explores the simultaneous recovery of both nutrients, addressing a critical gap in the existing literature [28]. Hofmann *et al.* [29] analysed the potential for nutrient recovery from wastewater using an adsorption kinetics approach. Panasiuk [30] examined the mechanism of phosphorus removal using magnetite as the foundation for developing an isotherm model. Moreover, Silva *et al.* [31] analysed the nutrient recovery capacity using microalgae in wastewater systems.

Several previous studies have served as a crucial foundation for the present research, such as Wu and Vaneeckhaute [3], who examined nutrient recovery technologies from wastewater and emphasised the superiority of adsorption as a simple yet effective method. According to Achilleos *et al.* [6], struvite precipitation is not only a waste treatment technique, but also a circular economic opportunity. Koulouri *et al.* [7] demonstrated the potential for nutrient recycling from faecal waste through biochar, discovering that nitrogen and phosphorus could

be enriched into the biochar via adsorption and precipitation, making it a valuable product for agricultural applications. Gong *et al.* [32] demonstrated that modified biochar has a higher ability to adsorb ammonium than phosphate. Meanwhile, Jiang *et al.* [33] asserted that the characteristics of magnesium-based biochar heavily influence the adsorption capacity of nitrogen and phosphorus from wastewater.

The urgency of recovering phosphorus is underscored by its finite availability, as evidenced by [34], and escalating demand in agriculture [35]. The traditional dependence on mined phosphate rock should be replaced by a more sustainable material balance that can meet the demand for phosphates in an equally sustainable manner. Likewise, nitrogen emission from agricultural runoff leads to agricultural and environmental inefficiencies [36]. By integrating nutrient recovery into wastewater treatment, the present study not only tackles water pollution but also offers a sustainable pathway for producing nutrient-enriched biochar as a fertiliser substitute [37]. Such innovations hold promise for reducing dependence on non-renewable resources [38] and enhancing agricultural productivity [39]. The study supports global sustainability goals related to decreasing waste, increasing resource recovery, and encouraging green technologies. Through novel biochar technologies, the investigation leads to efficient, up-scalable and sustainable wastewater treatment systems. Ultimately, it underscores the promise of the circular economy as a viable response to environmental challenges and a driver for sustainable development.

Unlike a previous study by Wijaya, which tested the performance of biochar on synthetic waste under controlled laboratory conditions [40], the present research introduces novelty by examining magnesium-activated biochar derived from temple waste directly on real wastewater from four stabilisation ponds in Bali. The use of real wastewater allows for the identification of the impact of heterogeneous waste composition on adsorption capacity and rate, a factor not extensively explored in previous studies. Additionally, the study emphasises the optimisation of biochar activation conditions across varying pH levels, resulting in biochar with more stable and sustainable adsorption performance. Hence, the findings not only strengthen the scientific foundation regarding the mechanisms of dual adsorption of ammonium and phosphate but also present a solution based on local wisdom within the framework of a circular economy, relevant for sustainable waste management in tropical tourism regions.

METHODS

A laboratory experimental method was employed to evaluate the effectiveness of magnesium-activated biochar derived from temple waste in removing ammonium and phosphate from wastewater. The main procedures included biochar preparation, activation, batch adsorption tests, and analytical evaluation. Each step is described in the following sections.

Preparation of Magnesium-Activated Temple Waste Biochar

The biochar was created using refuse-derived fuel made from waste materials from ceremonial temples. The raw materials underwent cleaning, drying, and grinding to achieve consistent particle dimensions. These processed materials were formed into briquettes and subjected to thermal decomposition in a controlled-atmosphere furnace at 500 °C for 2 hours, with a restricted oxygen supply, to achieve thorough carbon conversion. The next step involved activating the biochar with a solution of magnesium chloride ($MgCl_2$) at a concentration of 200 mg/L. The optimum pH was determined by an experiment on biochar activation at various pH levels, including pH 5, 7, and 9. Each pH buffer received a 1 g sample of biochar, with the concentration of $MgCl_2$ determined using ethylenediaminetetraacetic acid (EDTA) sodium salt at a pH range of 8 to 9. The biochar was activated under ideal pH conditions for subsequent adsorption testing. The mixture was subjected to constant stirring for 24 hours at room

temperature to facilitate the integration of magnesium. Furthermore, the biochar was filtered out from the mixture, washed with distilled water to remove any residual magnesium chloride, and dried at 105 °C for 12 hours until it reached a constant weight. The magnesium-infused biochar was placed in airtight containers for later usage.

Batch Experiments

Wastewater samples used in the study were taken from four different stabilisation ponds (numbered 1 to 4) at the local wastewater treatment plant in the south of Bali Island, Indonesia. The stabilisation ponds are utilised to treat the domestic wastewater from the surrounding hotels. The wastewater in these ponds typically contains elevated concentrations of nutrients, including ammonium (NH_4^+) and phosphate (PO_4^{3-}), which are the target contaminants. Samples of approximately 2 L of wastewater were collected from each stabilisation pond to examine the variation in nutrient concentrations. Each sample was filtered to remove larger particulates before performing the adsorption experiments.

The adsorption process was monitored using smaller wastewater samples of 250 mL, placed in four beakers, at two different contact times: 30 min and 60 min. After adding an activated biochar mass of 0.5 g, each beaker was shaken at a constant speed (80 rpm) to ensure uniform distribution of biochar throughout the solution. At the end of the sorption experiment, the biochar was filtered out. The levels of ammonium and phosphate in the solution were measured using UV-Vis spectrophotometry following established protocols. Spectrophotometric measurements were calibrated using standard solutions, and quality control procedures such as duplicate testing and blank utilisation were implemented to minimise the potential for analysis errors. The method was validated through replicate testing, the use of an internal standard, and blank testing to ensure the reliability of the results.

Research Flow

Figure 1 presents a general overview of the research methodology, illustrating the overall flow of the experiment, from sample collection to adsorption testing and data analysis.

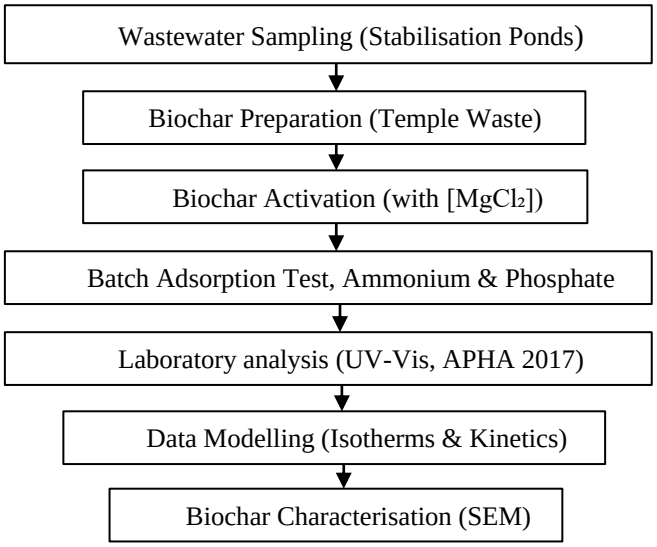


Figure 1. Schematic diagram of the research flow

The research procedure consisted of several stages, including wastewater sampling from the stabilisation pond, biochar preparation using temple waste, biochar activation with magnesium chloride, and batch adsorption testing for ammonium and phosphate. Laboratory analysis was performed using UV-Vis spectrophotometry in accordance with the American Public Health Association (APHA) guidelines (2017) **[41]** to ensure accuracy and

comparability at the international level. The measurements were followed by data modelling through isotherm and kinetic approaches, and final biochar characterisation using Scanning Electron Microscopy (SEM).

Analytical Equations

The biochar's ability to adsorb ammonium or phosphate per unit mass, known as the adsorption capacity (q_e), was calculated using eq. (1):

$$q_e = \frac{(C_0 - C_e) \times V}{m} \quad (1)$$

The adsorption capacities were determined for both ammonium and phosphate in each stabilisation pond sample, and the results were compared across different contact times (30 and 60 min). The rate of adsorption correlates with the speed at which the biochar adsorbs the adsorbate (ammonium or phosphate). The adsorption rate constant (k) was calculated using the second-order kinetic model. The mathematical expression for the model is given in eq. (2):

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

The adsorption data for both ammonium and phosphate were analysed using isotherm models to assess the adsorption equilibrium and capacity of biochar. The analysis utilised two commonly applied theoretical frameworks: Langmuir and Freundlich. The Langmuir framework is based on the premise of single-layer adsorption occurring on a surface containing a limited number of binding sites. In this case, the Langmuir adsorption equation can be expressed as in eq. (3):

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

The Freundlich model accounts for adsorption on heterogeneous surfaces with site-specific energy variations. It is defined by eq. (4):

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

The selection of the Langmuir and the Freundlich isotherm models is based on their relevance in explaining the mechanism of nutrient adsorption. The Langmuir model emphasises monolayer adsorption processes on homogeneous surfaces, while the Freundlich model is more suitable for heterogeneous surfaces with variations in binding energy. Similarly, first-order and second-order kinetic models are used to evaluate adsorption rates, with the second-order model often indicating the involvement of chemisorption mechanisms. Two models were applied to analyse the data obtained from the adsorption tests, aiming to determine the capacity and strength of adsorption for ammonium and phosphate. The model that best matched the collected data was chosen for further investigation.

The research focused on studying the progress of ammonium and phosphate absorption using both initial-order and secondary-order models. In accordance with the initial-order model, the speed of absorption is linked to the variation in concentration of the adsorbate over time, as shown in eq. (5):

$$\ln(C_0 - C_t) = \ln C_0 - k_1 \times t \quad (5)$$

The second-order kinetics was used to explain the adsorption process [42], showing that the rate of adsorption is equal to the square of the adsorbate concentration [43]. This relationship is included in the adsorption rate term of eq. (2). The second-order model is preferable in cases where the adsorption process is influenced by chemisorption. Using statistical regression methods [44], the experimental findings for ammonium and phosphate uptake were examined to determine the rate constants (k) and equilibrium adsorption capacities (q_e). The correlation coefficients (R^2) derived from evaluating the Langmuir and the Freundlich isotherms, as well as the first-order and second-order kinetic frameworks, were employed to assess the precision of the model fitting [45]. The theoretical model with the highest R^2 coefficient was considered the most precise explanation of how nutrients are adsorbed. Additionally, SEM was employed to investigate the surface texture and structural features of the biochar before and after activation, as well as after the adsorption procedure.

Although SEM provides a visual representation of biochar morphology and porosity, other characterisations such as Fourier Transform Infrared Spectroscopy (FTIR) and Brunauer-Emmett-Teller (BET) surface area analysis are commonly used to assess functional groups and specific surface area. The present study prioritised SEM due to its focus on changes in morphological structure. A recommendation for further research is to integrate FTIR and BET for a more comprehensive understanding of adsorption mechanisms.

RESULTS AND DISCUSSION

The following section presents the experimental results concerning the development and activation of magnesium-activated biochar made from temple waste, as well as its effectiveness in removing ammonium and phosphate from wastewater. The findings have been categorised into various subsections, including the activation process of biochar, its efficacy in nutrient adsorption, modelling of kinetics and isotherms, capacity and rate of adsorption, and morphological analysis using Scanning Electron Microscopy.

Biochar Activation

According to **Figure 2**, the graph depicting magnesium concentration over time during the biochar activation process under different pH environments (pH 5, pH 7, and pH 9) reveals distinct trends in magnesium retention, thus indicating distinct activation patterns. At pH 5, the magnesium concentration starts at approximately 190 mg/L, with a rapid decline observed within the first 20 min, ultimately stabilising around 110 mg/L by the 90-minute mark. A similar initial drop is observed at pH 9, where the concentration decreases sharply in the early stages but shows a recovery, stabilising at approximately 130 mg/L by the end of the process. In contrast, at pH 7, the magnesium concentration initially shows a more gradual decline, followed by a steady increase towards the latter stages of the activation process, reaching approximately 130 mg/L by the end of 90 minutes.

The sharp initial decline in magnesium concentration observed at pH 5 and pH 9 suggests that biochar activation at these pH levels leads to a significant early-stage uptake or adsorption of magnesium. These early decreases can be attributed to the biochar's enhanced adsorption performance at both low and high pH levels, where the ion exchange rates are higher during the initial stages of activation. However, the rate of change slows considerably after the first 20 min, indicating that the biochar reaches a saturation point for magnesium adsorption.

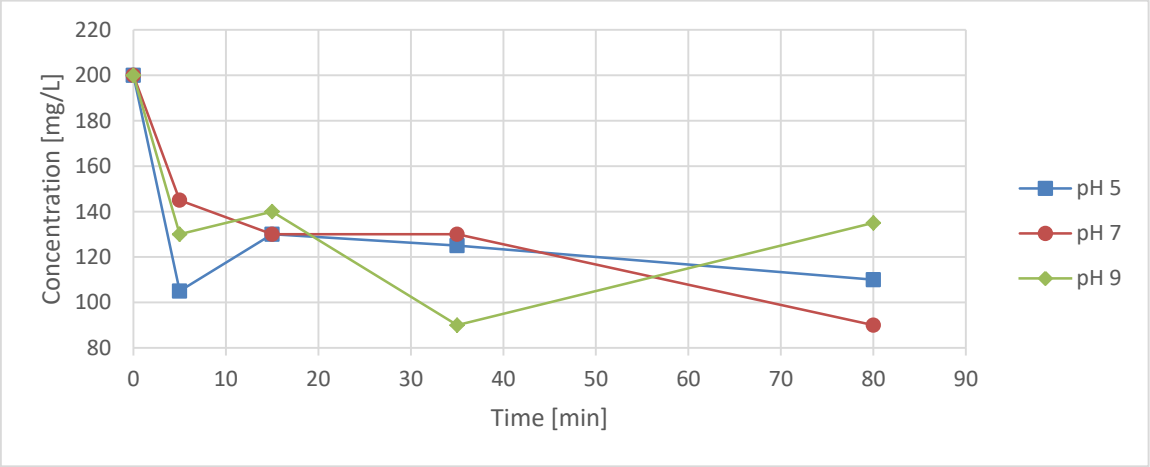


Figure 2. Concentration of MgCl2 during the biochar activation

At a pH of 7, the concentration of magnesium sharply decreased during the first 5 minutes, then stabilised at around 130 mg/L between 20–40 min and gradually reduced further to about 90 mg/L at the end of 80 min. The evidence suggests that neutral pH conditions provide a relatively stable retention phase followed by a gradual decline, indicating effective ion exchange and cation adsorption over time compared to acidic (pH 5) or alkaline (pH 9) conditions [32].

These findings are consistent with existing literature on the impact of pH on biochar's ion exchange capacity. Jiang *et al.* [33] demonstrated that the adsorption kinetics of biochar are influenced by pH conditions, with neutral pH providing the ideal situation for cation exchange and nutrient retention. Meanwhile, Zhao *et al.* [46] found that acidic conditions (pH 5) enhance the initial absorption of magnesium; however, the stability of the adsorption decreases over time. Conversely, basic conditions (pH 9) also show high initial uptake but with lower retention compared to neutral pH. Hence, a neutral pH can be considered the optimal condition for maintaining the stability of magnesium adsorption on biochar. These results suggest that biochar activated at pH 7 offers the best balance of magnesium retention over time, making it the optimal condition for using biochar in applications requiring long-term nutrient retention.

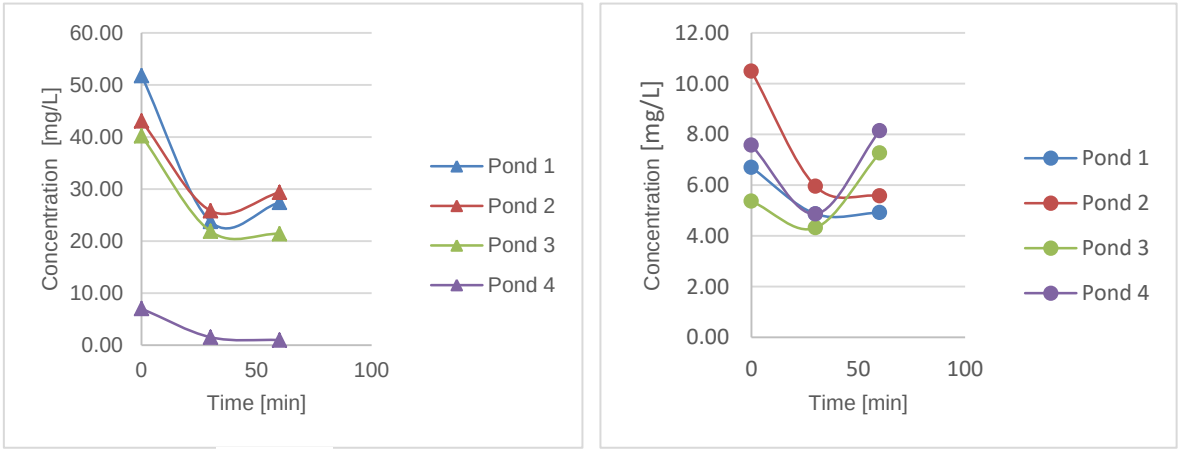
In summary, pH 7 is identified as the most effective condition for maintaining higher and more stable magnesium concentrations throughout the biochar activation process. The results highlight the importance of pH in optimising biochar's nutrient retention capabilities, supporting the notion that neutral pH environments are most beneficial for maximising magnesium adsorption and retention.

Nutrient Adsorption

The findings highlight the importance of optimising contact time and biochar dosage to enhance the adsorption performance for ammonium and phosphate removal using biochar sourced from stabilisation pond wastewater. The analysis examined the impact of these two factors on the outcomes of ammonium and phosphate adsorption rates and capacities in samples collected from an actual wastewater in a stabilisation pond. The changes in nutrient concentration during adsorption for ammonium and phosphate in four stabilisation ponds are summarised in **Figure 3**. The figure highlights the reduction in concentration over contact time and variations among ponds.

For ammonium, all ponds exhibit a sharp reduction within the first 30 min, followed by stabilisation or a slight rebound at 60 min. Pond 1 and Pond 2 decline from above 40 mg/L to around 25 mg/L in the first 30 min, then increase slightly toward 60 min, while Pond 3 shows a similar pattern with only minor fluctuation. Pond 4 experiences the most significant decline, dropping from about 10 mg/L to nearly zero and remaining stable thereafter. These results

confirm that biochar is highly effective in reducing ammonium levels during the initial contact period, with subsequent changes reflecting the attainment of adsorption equilibrium. The linear regression results (R^2 values) for ammonium adsorption further support the observation, showing relatively high values for most ponds, particularly Pond 1 (R^2 = 0.6389), which indicates a moderate correlation between time and ammonium reduction. For phosphate, concentrations also decrease during the first 30 minutes across all ponds, with the most pronounced reduction observed in Pond 2 (from approximately 10 mg/L to 5 mg/L). However, phosphate levels tend to increase slightly after 30 min in most ponds, suggesting partial desorption or equilibrium adjustment during the later stage of the process.



(a) (b)

Figure 3. The nutrient concentration during the adsorption in wastewater: ammonium (a), phosphate (b)

Similarly, phosphate adsorption also demonstrates a strong initial reduction in concentration during the first 30 min, followed by a plateau or a slower decline after 60 min. The phosphate concentrations in the four ponds (Ponds 1, 2, 3, and 4) exhibit varying rates of decline, with Pond 1 showing a more pronounced reduction (R^2 = 0.7687). As such, like ammonium, phosphate is adsorbed more rapidly during the initial stages, with adsorption slowing as the biochar surface becomes saturated. These trends suggest that nutrients such as ammonium and phosphate are absorbed more rapidly during the initial stage, due to the abundance of active sites still available on the biochar surface. Agusriyadin [47] explained that the acceleration in the adsorption rate during the initial phase is a result of the high presence of pores and active surface area on the absorbing material. Meanwhile, Setyorini *et al.* [48] further explained that once the sites are filled, the rate of adsorption will decrease as the available absorption sites become limited. Such a phenomenon helps clarify the pattern of a rapid absorption rate at the beginning, followed by a slowing down after reaching equilibrium. The decrease in adsorption speed following the initial phase is likely due to the active sites becoming saturated, resulting in a reduction of available unoccupied sites for additional adsorption.

Enhancing the quantity of biochar results in a greater ability to adsorb both ammonium and phosphate, as it provides a larger surface area for ion exchange and adsorption to occur [49]. The higher mass of biochar provides more adsorption sites, promoting a higher rate of nutrient removal from the solution, as confirmed by the data obtained in the research. Results indicate that biochar is an effective adsorbent for reducing nutrient concentrations in wastewater, with a greater biochar mass leading to enhanced nutrient removal. Ammonium is shown to be adsorbed faster and with better results than phosphate in the stabilisation pond samples when comparing their adsorption rates. The accelerated removal of ammonium during the initial 30 min can be attributed to its relatively small ionic size, which enables more efficient interaction with and adsorption onto the biochar surface. In phosphate adsorption, larger and more

complex ionic structures exhibit slower adsorption kinetics. Such a difference in adsorption rates can be explained by the distinct mechanisms of interaction between biochar and these two nutrients. Wu & Vaneeckhaute [3] reported that ammonium is primarily absorbed through electrostatic forces and ion exchange mechanisms. Andreas [50] discovered that phosphate can interact with the surface of biochar through a complex surface complexation process, forming specific chemical bonds. Furthermore, Krishna Murthy *et al.* [51] found that under particular conditions, phosphate can also undergo precipitation and electrostatic adsorption. The combination of these three mechanisms explains why phosphate has slower absorption kinetics compared to ammonium.

These findings are consistent with research by Gong *et al.* [32], who suggested that the smaller ion radii and higher charge density enable ammonium ions to interact more rapidly with the biochar surface. Jiang *et al.* [33] also stated that biochar can significantly reduce the concentration of ammonium and phosphate, but the efficiency of ammonium removal is notably higher. Koulouri *et al.* [7] found that increasing the biochar mass leads to greater adsorption efficiency for both nutrients. Overall, these studies reinforce the findings of the current investigation, which suggest that ammonium is absorbed more quickly and effectively than phosphate in real wastewater. The increased biochar dosage provides more active sites for ion exchange and adsorption, which results in greater nutrient removal. The observed correlation between biochar dosage and nutrient adsorption in present research supports these findings and emphasises the importance of optimising biochar mass for effective nutrient removal in wastewater treatment. Overall, the findings demonstrate that biochar effectively adsorb and lower levels of ammonium and phosphate in actual wastewater samples taken from stabilisation ponds. The adsorption process is highly dependent on both contact time and biochar dosage, with ammonium being adsorbed more rapidly than phosphate. Increasing biochar dosage enhances the adsorption capacity for both nutrients, confirming that biochar is a viable method for nutrient removal from wastewater [52]. The findings herein are in line with literature and have confirmed biochar to be a promising sustainable technology for wastewater treatment and nutrient recovery for environmental applications.

Kinetic and Isotherm Analysis of the Nutrient Adsorption

Kinetic analysis enables the examination of the speed and processes involved in the absorption of ammonium and phosphate by biochar. By applying both first-order and second-order kinetic models to the experimental data for ammonium and phosphate adsorption, the dominant adsorption mechanism can be identified. A kinetic and isothermal analysis is presented below to clarify the interactions between ammonium and phosphate and the biochar surface, as well as the mechanisms controlling nutrient sorption.

Ammonium adsorption kinetics. In samples taken from stabilisation ponds, the concentration of ammonium decreases rapidly during the first 30 min of contact, before tapering off and reaching a steady state after 60 min. The information obtained from the study was evaluated using two different kinetic models. The results indicate that the second-order kinetics model provided a more accurate fit with a higher R^2 value. **Figure 4** displays the first-order and second-order kinetic reactions for ammonium uptake in wastewater samples from ponds 1 through 4 (P1–P4). The absorption rate in P3 showed the highest value, at 0.21 mg/min, while the lowest was found in P1, at 0.03 mg/min. The data indicate that ammonium removal follows a chemisorption mechanism, with the chemical bonding between ammonium ions and the biochar surface controlling the reaction rate. The biochar materials commonly exhibit second-order kinetic behaviour during ammonium adsorption due to their interactions with surface reactive groups and ion-exchange mechanisms.

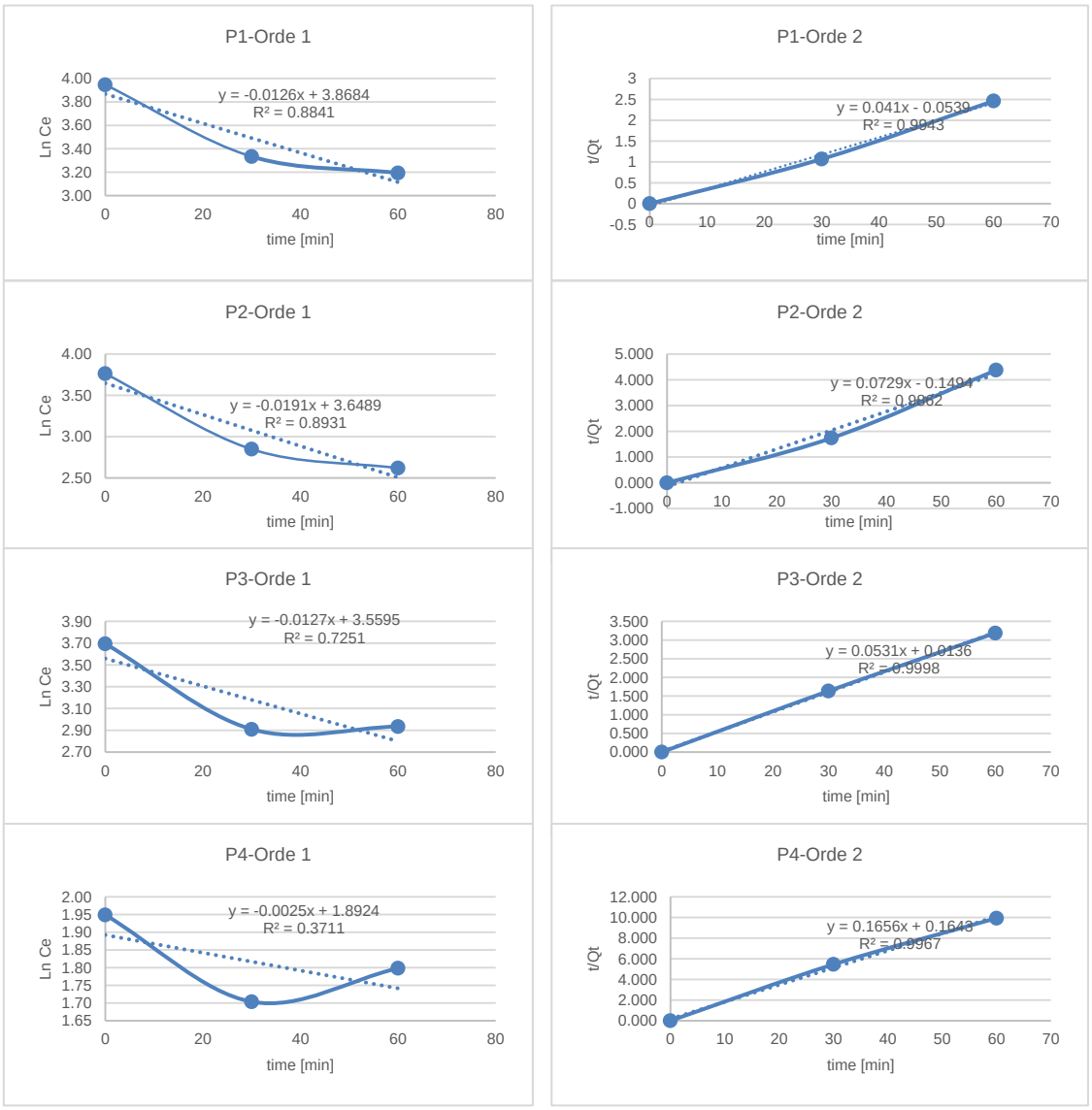


Figure 4. Reaction kinetics of first and second order for ammonium removal from wastewater across pond systems P1 to P4

The experimental results on the removal of ammonium from wastewater samples indicate a suitable quality and varying concentration levels across four ponds. After examining the kinetic performance for ammonium, the following section deliberates on phosphate adsorption to pinpoint differences in the rate and mechanism of adsorption.

Phosphate adsorption kinetics. During the phosphate adsorption process, a decrease in concentration is initially observed, followed by a gradual slowing of the adsorption rate after 30 min, similar to that of ammonium. The second-order model was found to be more accurate than the first-order model in predicting the adsorption process. The evidence suggests that the process of phosphate binding to biochar is similar to chemisorption, but occurs more slowly than with ammonium. The reason for the slowdown in phosphate absorption is that the phosphate ion is larger and interacts with the biochar surface in a complex manner, requiring more time to form solid bonds [53]. The results emphasise that the absorption of ammonium and phosphate by biochar follows a second-order kinetic model, where chemical adsorption plays a key role in the removal process.

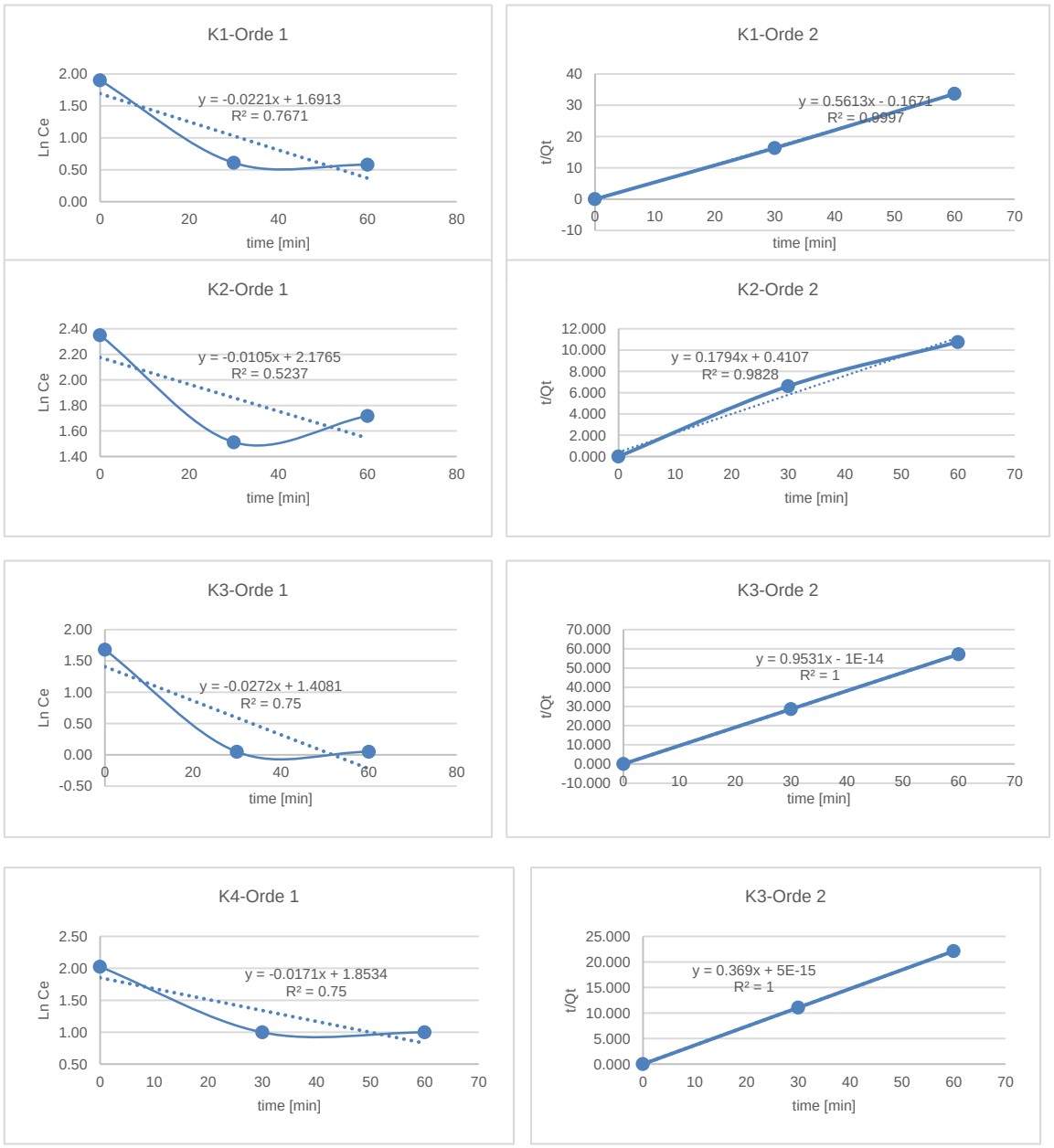


Figure 5. Reaction kinetics of first and second order for phosphate adsorption in the wastewater from pond 1 (P1) to pond 4 (P4).

Figure 5 displays the first-order and second-order kinetic reactions for phosphate removal from wastewater samples across pond systems 1 through 4 (P1-P4)**,** indicating that adsorption follows pseudo-second-order behaviour consistent with chemisorption. The phosphate absorption rate in P3 showed the highest value, at 6.49 mg/min, while the lowest was found in P2, at 0.08 mg/min. The initial rapid adsorption, followed by a slower phase, suggests that both ammonium and phosphate interact strongly with the biochar surface; however, phosphate requires more time to fully adsorb due to its larger ion size and different chemical behaviour.

After the kinetic evaluation, the research proceeded by analysing the adsorption equilibrium behaviour through isotherm modelling.

Ammonium adsorption isotherm. The Freundlich model demonstrated the highest level of accuracy for capturing ammonium adsorption, with an R^2 value up to 0.999. The results show that the biochar surface contains a range of adsorption sites with varying binding strengths. The Freundlich constant for ammonium indicates a moderate adsorption capacity, with P1 exhibiting the highest absorption capacity (24.39 mg/g) and P4 showing the lowest capacity

(6.04 mg/g). The n-value less than 1 suggests that the adsorption of ammonium is not highly favourable under the specific conditions of the present study. The observation corroborates the conclusions of Ren [54], who reported similar findings for ammonium adsorption on biochar, indicating that multiple adsorption sites are involved; however, the adsorption efficiency could be improved with optimised biochar surface properties. The Langmuir model was less successful at fitting the ammonium adsorption data, with low R^2 values, indicating that ammonium adsorption on biochar does not follow monolayer adsorption [24]. Instead, the data imply that ammonium is attracted to various layers, showing that biochar's surface is diverse and has multiple binding sites for adsorption.

To complement the results of ammonium adsorption, the adsorption of phosphate was also analysed using the same isotherm model for comparative evaluation.

Phosphate adsorption isotherm. The phosphate absorption is more in agreement with the Freundlich isotherm ($R^2 > 0.98$), suggesting that multiple absorption sites with varying energy levels influence phosphate absorption on biochar. The Freundlich constant for phosphate absorption in P2 was 5.57 mg/g, which is lower than that of ammonium and the highest among the other ponds. Phosphate removal by biochar involves greater complexity and lower efficiency due to its larger ion dimensions [32] and the requirement for multiple binding sites to achieve effective attachment [55]. The Langmuir model did not accurately represent the phosphate absorption, indicating that phosphate may not adhere to just one layer on biochar but forms several layers during the adsorption process. The findings coincide with the conclusions drawn by other researchers. Likewise, the Freundlich model is commonly used to explain the adsorption of nutrients (such as ammonium and phosphate) on biochar [32], attributed to the diverse surfaces of biochar [56]. Furthermore, a better fit was obtained with the Freundlich isotherm than with the Langmuir model, indicating that the biochar surface is non-uniform and characterised by a diversity of adsorption site energies.

The research findings indicate that biochar can effectively decrease the levels of ammonium and phosphate in actual wastewater collected from stabilisation ponds. The examination of kinetics revealed that the absorption of both nutrients follows second-order kinetics, indicating that chemisorption has a significant impact on the process. The adsorption behaviour of ammonium and phosphate ions on biochar surface is effectively explained by the Freundlich isotherm model, indicating the heterogeneous nature of the surface capable of adsorbing ions in various layers. According to the findings, biochar exhibits excellent potential as a substance for purifying wastewater [37], particularly in adsorbing nutrients [22]. However, enhancing biochar properties and boosting its ability to adsorb pollutants by modifying the surface or activating it could improve its effectiveness in environmental tasks, such as recovering nutrients and controlling pollution.

Ultimately, the rate and adsorption capacity are summarised to assess the overall performance of biochar adsorption under real wastewater conditions.

Adsorption rate and capacity. The adsorption capacity and rate for ammonium and phosphate were examined using biochar applied to real wastewater samples sourced from the stabilisation ponds. The kinetics and adsorption isotherms provided valuable insights into the performance of biochar as an adsorbent for reducing nutrient levels in wastewater.

The adsorption capacity refers to the maximum amount of ammonium and phosphate that biochar can adsorb at equilibrium, and it is crucial for evaluating the efficiency of biochar in wastewater treatment. The results show that biochar exhibited varying adsorption capacities depending on the pond sample and the nutrient involved. The absorption capacity of magnesium-activated biochar for ammonium and phosphate in wastewater samples is summarised in **Table 1**.

Table 1. Adsorption capacity of biochar in wastewater

Pond	Ammonium adsorption capacity [mg/g]	Phosphate adsorption capacity [mg/g]
Pond 1	24.39	1.78
Pond 2	13.72	5.57
Pond 3	18.83	1.05
Pond 4	6.04	2.71

Among the sampled ponds, Pond 1 demonstrated the greatest ammonium adsorption capacity (24.39 mg/g), while Pond 3 recorded a moderately lower value of 18.83 mg/g. In contrast, Pond 4 has the lowest ammonium adsorption capacity at 6.04 mg/g. The highest phosphate adsorption capacity was also observed in Pond 2 (5.57 mg/g), whereas Pond 3 exhibited the lowest capacity for phosphate at 1.05 mg/g. These differences can be attributed to the varying biochar surface characteristics in each stabilisation pond, as well as differences in the composition and characteristics of the wastewater from each pond, which can influence the availability of adsorption sites. Biochar with a higher specific surface area and more active sites tends to exhibit better adsorption capacities for nutrients like ammonium and phosphate [52].

The rate of adsorption signifies how quickly biochar adsorbs ammonium and phosphate. The adsorption rates for ammonium and phosphate were calculated based on the second-order model, and the reaction rate constants (k) are summarised in Table 2. The constants of adsorption rate derived from the pseudo-second-order kinetic model indicate the variations in adsorption speed among different pond samples.

Table 2. Adsorption rate of biochar in wastewater

Pond	Ammonium rate constant [mg/min]	Phosphate rate constant [mg/min]
Pond 1	0.03	1.89
Pond 2	0.04	0.08
Pond 3	0.21	6.49
Pond 4	0.17	0.91

Based on Table 2, the adsorption rate for ammonium is relatively low across all ponds, with the highest rate constant observed in Pond 3 (0.21 mg/min), while Pond 1 has the lowest rate constant at 0.03 mg/min. In contrast, the phosphate adsorption rate varies more widely, with Pond 3 showing the highest phosphate rate constant (6.49 mg/min), suggesting that Pond 3 has a faster phosphate uptake rate compared to the other ponds. The evidence is consistent with the higher phosphate adsorption capacity observed in Pond 2, which has a significantly lower rate constant (0.08 mg/min) for phosphate adsorption. The adsorption rate constant (k) is a crucial parameter, as it indicates how quickly the adsorbent can remove contaminants from the solution. Higher values of k indicate faster adsorption processes.

These findings align with previous studies on the absorption capacity of biochar for ammonium and phosphate. Gong *et al.* [32] noted that the adsorption capacity of biochar for ammonium ranges from 5 to 30 mg/g, depending on the type of biochar and solution composition. Wijayanti & Kurniawati [45] discovered that the Freundlich isotherm model is the most appropriate for explaining nutrient adsorption in real wastewater because biochar surfaces are heterogeneous. Setyorini *et al.*[48] emphasised that the heterogeneity creates variations in binding energy between adsorption sites that influence the absorption rate. The

consistency of these findings suggests that the dominant mechanism in the adsorption process is chemisorption, characterised by a Freundlich isotherm pattern. The experimental results demonstrate the adsorption capacity and adsorption rate of biochar for reducing ammonium and phosphate concentrations in real wastewater from stabilisation ponds. The findings suggest that biochar exhibits significant adsorption capacities, with Pond 1 showing the highest ammonium capacity and Pond 2 exhibiting the highest phosphate capacity. The adsorption rate constants confirm that biochar adsorption follows second-order kinetics, with Pond 3 showing the fastest adsorption for both contaminants.

The findings suggest that biochar has the potential to remove nutrients from wastewater effectively, and its effectiveness can be improved by adjusting the amount of adsorbent used and the duration of contact. Future studies should focus on enhancing the adsorption kinetics by modifying biochar properties to improve the adsorption efficiency for both ammonium and phosphate, thereby providing a sustainable solution for wastewater treatment and nutrient recovery.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to analyse the visual characteristics of biochar before and after activation, as well as after adsorbing ammonium and phosphate from real wastewater samples. SEM pictures offer in-depth knowledge into the texture, porosity, and microstructure of biochar [13], which play a significant role in determining its ability to adsorb pollutants in water treatment processes [16].

The SEM analysis results indicated that the biochar before the activation process exhibited a relatively rough and irregular surface with imperfectly open pores and fragmented materials. The condition rendered the biochar appearing smoother and less porous compared to activated biochar, thus reducing the number of active sites for adsorption as well. These findings align with previous studies, which reported that non-activated biochar has limitations in terms of functional groups and underdeveloped pore structures, resulting in low effectiveness in removing pollutants such as ammonium and phosphate. The minimal presence of micro and macropores further reinforced the indication that non-activated biochar is less efficient in absorbing nutrients from wastewater [57].

After the activation process with magnesium, the biochar surface undergoes significant changes, as evidenced by an increase in pore size, a rougher texture, and an increase in small pores. The addition of magnesium is believed to play a role in expanding the surface area and enriching the presence of functional groups on biochar. These structural changes result in increased reactivity of biochar, enhancing its ability to adsorb ammonium and phosphate ions more effectively. The enhancement of the external texture is a common trait of biochar that has been activated through various means, such as physical or chemical processes [39] that boost its porosity and the number of active sites available [58]. The SEM analysis results indicate that a rougher texture and larger pores are closely related to the increase in biochar adsorption capacity. Muscarella *et al.* [10] demonstrated that chemically activated zeolite has higher porosity, thereby enhancing its ability to absorb ammonium. Alsulaili *et al*. [13] suggested that a wide porous structure provides greater opportunities for ion exchange and contaminant binding on the surface of biochar. As such, morphological changes due to the activation process directly contribute to increased adsorption efficiency.

Figure 6 shows the SEM analysis of biochar after adsorption in real wastewater from stabilisation ponds. The SEM images reveal a notable difference in the biochar structure after adsorption, with a visible accumulation of adsorbates on the biochar surface. The pores appear to be partially blocked, and some adsorption sites seem to have been filled with the adsorbed nutrients, further demonstrating the biochar's effectiveness in removing ammonium and phosphate from the wastewater. The surface change is indicative of adsorption saturation, where the biochar surface has been partially occupied by ammonium and phosphate ions. The

partial blockage of pores and the presence of adsorbed material suggest that the biochar has effectively captured these contaminants [33]. The SEM image clearly illustrates the surface roughness, pore blockage, and adsorbate accumulation.

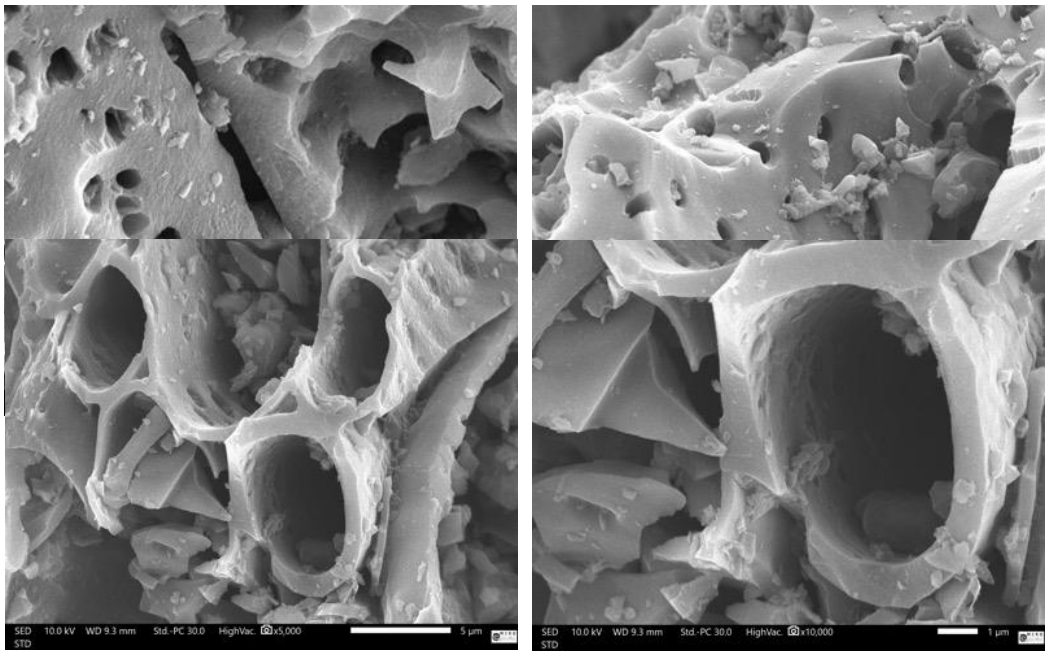


Figure 6. Biochar after adsorption

The reuse of treated wastewater from temples enriched with ammonium and phosphate has significant socio-economic potential in tropical regions such as Bali. The recovered nutrients can be transformed into affordable biochar fertilisers, reducing dependence on chemical fertilisers, supporting small-scale farmers, and strengthening circular economy practices based on local wisdom. From a policy perspective, the authorities can facilitate the implementation of such technology through decentralised processing regulations, fiscal incentives, or public-private partnerships. The initiative aligns with the Sustainable Development Goals (SDGs), particularly SDGs 6, 11, and 12. It is relevant for South Asian regions with significant potential for utilising temple waste to support community economic resilience and environmental protection.

CONCLUSIONS

The findings confirm that magnesium-activated biochar derived from temple waste is an effective and sustainable adsorbent for recovering ammonium and phosphate from wastewater. Adsorption kinetics conformed to the pseudo-second-order model, indicating chemisorption dominance, while equilibrium data were best described by the Freundlich isotherm, reflecting surface heterogeneity and multilayer adsorption. Evaluation of multiple wastewater sources revealed variations in both adsorption capacity and rate, with the adsorption rate constant for phosphate reaching significantly higher values in specific samples, demonstrating the potential for rapid nutrient uptake under optimal conditions. These variations underline the importance of characterising local wastewater and tailoring biochar application accordingly. The results reinforce the feasibility of utilising locally sourced organic waste for nutrient recovery, thereby contributing to environmental protection, promoting resource circularity, and facilitating the development of cost-effective wastewater treatment solutions.

In addition to its technical performance, the findings emphasise the socio-economic and policy dimensions of utilising temple waste. The conversion of temple waste into activated

magnesium biochar not only supports nutrient recovery but also creates local economic value through the provision of affordable organic fertilisers, reducing costs for farmers, and strengthening cultural sustainability through circular economy practices based on local wisdom. Hence, policymakers in the South Asian region are encouraged to adopt a supportive regulatory framework, including incentives and community-based programs, to promote the adoption of biochar-based wastewater treatment technologies. The integration underscores the socio-economic and cultural significance of wastewater treatment, rendering it a vital component of sustainable resource management strategies in the region.

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NOMENCLATURE

Symbols

q_e	Adsorption capacity	[mg/g]
C_0	Initial concentration of the adsorbate	[mg/L]
V	Volume of the solution	[L], [mL]
m	Mass of the biochar	[g]
q_t	Amount of adsorbate adsorbed at time t	[mg/g]
k	Rate constant	[mg/g·min], [-]
t	Time	[min]
C_e	Equilibrium concentration of the adsorbate	[mg/L]
Q_m	Maximum adsorption capacity	[mg/g]
K_L	Langmuir constant related to adsorption energy	[L/mg]
K_f	Freundlich constant, adsorption capacity	[mg/g]
C_t	Concentration of the adsorbate at time t	[mg/L]
k_1	Rate constant for a first-order reaction	[1/min]
n	Freundlich constant, adsorption intensity	[-]
P1	Pond 1	
P2	Pond 2	
P3	Pond 3	
P4	Pond 4	

Abbreviations

RDF	Refuse-Derived Fuel
SEM	Scanning Electron Microscopy
EDTA	Ethylenediaminetetraethanoic acid

REFERENCES

1. Kaown, D., Koh, D.-C., Mayer, B., Mahlknecht, J., Ju, Y., Rhee, S.-K., Kim, J.-H., Park, D. K., Park, I., Lee, H.-L., Yoon, Y.-Y., & Lee, K.-K. (2023). Estimation of nutrient sources and fate in groundwater near a large weir-regulated river using multiple isotopes and microbial signatures. *Journal of Hazardous Materials*, *446*, 130703. https://doi.org/10.1016/j.jhazmat.2022.130703
2. Yates, A. G., Brua, R. B., Friesen, A., Reedyk, S., & Benoy, G. (2022). Nutrient and suspended solid concentrations, loads, and yields in rivers across the Lake Winnipeg Basin: A twenty year trend assessment. *Journal of Hydrology: Regional Studies*, *44*, 101249. https://doi.org/10.1016/j.ejrh.2022.101249

3. Wu, H., & Vaneeckhaute, C. (2022). Nutrient recovery from wastewater: A review on the integrated Physicochemical technologies of ammonia stripping, adsorption and struvite precipitation. *Chemical Engineering Journal*, *433*, 133664. https://doi.org/10.1016/j.cej.2021.133664
4. Proskynitopoulou, V., Vourros, A., Garagounis, I., Dimopoulos Toursidis, P., Lorentzou, S., Zouboulis, A., & Panopoulos, K. (2024). Enhancing nutrient and water recovery from liquid digestate: A comparative study of selective electrodialysis and conventional treatment methods. *Journal of Environmental Chemical Engineering*, *12*(3), 112675. https://doi.org/10.1016/j.jece.2024.112675
5. Howarth, R. W., & Marino, R. (2006). Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography*, *51*(1part2), 364–376. https://doi.org/10.4319/lo.2006.51.1_part_2.0364
6. Achilleos, P., Roberts, K. R., & Williams, I. D. (2022). Struvite precipitation within wastewater treatment: A problem or a circular economy opportunity? *Heliyon*, *8*(7), e09862. https://doi.org/10.1016/j.heliyon.2022.e09862
7. Koulouri, M. E., Templeton, M. R., & Fowler, G. D. (2024). Enhancing the nitrogen and phosphorus content of faecal-derived biochar via adsorption and precipitation from human urine. *Journal of Environmental Management*, *352*, 119981. https://doi.org/10.1016/j.jenvman.2023.119981
8. Dewi, D. F., & Masduqi, A. (2003). Penyisihan Fosfat Dengan Proses Kristalisasi Media Pasir Silika. *Jurnal Purifikasi*, *4*(4), 151–156.
9. Pinelli, D., Foglia, A., Fatone, F., Papa, E., Maggetti, C., Bovina, S., & Frascari, D. (2022). Ammonium recovery from municipal wastewater by ion exchange: Development and application of a procedure for sorbent selection. *Journal of Environmental Chemical Engineering*, *10*(6), 108829. https://doi.org/10.1016/j.jece.2022.108829
10. Muscarella, S. M., Badalucco, L., Cano, B., Laudicina, V. A., & Mannina, G. (2021). Ammonium adsorption, desorption and recovery by acid and alkaline treated zeolite. *Bioresource Technology*, *341*, 125812. https://doi.org/10.1016/j.biortech.2021.125812
11. Jagadeesh, N., & Sundaram, B. (2023). Adsorption of Pollutants from Wastewater by Biochar: A Review. *Journal of Hazardous Materials Advances*, *9*, 100226. https://doi.org/10.1016/j.hazadv.2022.100226
12. Ilori, A. O. A., Ogbonnaya, O. U., Asaolu, J. I., Shittu, O. S., & Fasina, A. S. (2023). Characterization of biochar and phosphorus adsorption in charnockite-originated soils. *Journal of the Saudi Society of Agricultural Sciences*, *22*(1), 54–61. https://doi.org/10.1016/j.jssas.2022.06.004
13. Alsulaili, A., Elsayed, K., & Refaie, A. (2024). Utilization of agriculture waste materials as sustainable adsorbents for heavy metal removal: A comprehensive review. *Journal of Engineering Research*, *12*(4), 691–703. https://doi.org/10.1016/j.jer.2023.09.018
14. Torres Castillo, N. E., Ochoa Sierra, J. S., Oyervides-Muñoz, M. A., Sosa-Hernández, J. E., Iqbal, H. M. N., Parra-Saldívar, R., & Melchor-Martínez, E. M. (2021). Exploring the potential of coffee husk as caffeine bio-adsorbent – A mini-review. *Case Studies in Chemical and Environmental Engineering*, *3*, 100070. https://doi.org/10.1016/j.cscee.2020.100070
15. Goldschmidt, A., & Buffam, I. (2023). Biochar-amended substrate improves nutrient retention in green roof plots. *Nature-Based Solutions*, *3*, 100066. https://doi.org/10.1016/j.nbsj.2023.100066
16. Susilawati, Sihombing, Y. A., Rahayu, S. U., Sembiring, Y. Y. B., Waldiansyah, L., & Irma, M. (2023). Filter material based on zeolite-activated charcoal from cocoa shells as ammonium adsorbent in greywater treatment. *South African Journal of Chemical Engineering*, *43*, 266–272. https://doi.org/10.1016/j.sajce.2022.11.006
17. Ribeiro, R. S., Rodrigues, R. O., Silva, A. M. T., Tavares, P. B., Carvalho, A. M. C., Figueiredo, J. L., Faria, J. L., & Gomes, H. T. (2017). Hybrid magnetic graphitic nanocomposites towards catalytic wet peroxide oxidation of the liquid effluent from a mechanical biological treatment plant for municipal solid waste. *Applied Catalysis B: Environmental*, *219*, 645–657. https://doi.org/10.1016/j.apcatb.2017.08.013

18. Lensoni, L., Lubis, Y. A., Setiawan, H., Hidayatullah, M., & Naira, A. Z. (2024). Identification of Mercury Content in Smallholder Gold Mining Well Water in the Working Area of UPTD Puskesmas Ujung Padang Rasian, South Aceh District. *Transpublika International Research In Exact Sciences*, *3*(2), 42–48. https://doi.org/10.55047/tires.v3i2.1207
19. Li, B., Jing, F., Hu, Z., Liu, Y., Xiao, B., & Guo, D. (2021). Simultaneous recovery of nitrogen and phosphorus from biogas slurry by Fe-modified biochar. *Journal of Saudi Chemical Society*, *25*(4), 101213. https://doi.org/10.1016/j.jscs.2021.101213
20. Zhang, W., Zhou, Z., An, Y., Du, S., Ruan, D., Zhao, C., Ren, N., & Tian, X. (2017). Optimization for zeolite regeneration and nitrogen removal performance of a hypochlorite-chloride regenerant. *Chemosphere*, *178*, 565–572. https://doi.org/10.1016/j.chemosphere.2017.03.091
21. Markou, G., Vandamme, D., & Muylaert, K. (2014). Using natural zeolite for ammonia sorption from wastewater and as nitrogen releaser for the cultivation of Arthrospira platensis. *Bioresource Technology*, *155*, 373–378. https://doi.org/10.1016/j.biortech.2013.12.122
22. Barbhuiya, S., Bhusan Das, B., & Kanavaris, F. (2024). Biochar-concrete: A comprehensive review of properties, production and sustainability. *Case Studies in Construction Materials*, *20*, e02859. https://doi.org/10.1016/j.cscm.2024.e02859
23. Shi, W., Lian, W., Tian, S., Gong, X., Yu, Q., Guo, Z., Zhang, X., Ma, B., Bian, R., Zheng, J., Cheng, K., & Pan, G. (2023). A review of agronomic and environmental properties of inorganic compounds in biochars. *Current Research in Environmental Sustainability*, *5*, 100226. https://doi.org/10.1016/j.crsust.2023.100226
24. Yang, H. I., Lou, K., Rajapaksha, A. U., Ok, Y. S., Anyia, A. O., & Chang, S. X. (2018). Adsorption of ammonium in aqueous solutions by pine sawdust and wheat straw biochars. *Environmental Science and Pollution Research*, *25*(26), 25638–25647. https://doi.org/10.1007/s11356-017-8551-2
25. Erdem, H. (2021). The effects of biochars produced in different pyrolsis temperatures from agricultural wastes on cadmium uptake of tobacco plant. *Saudi Journal of Biological Sciences*, *28*(7), 3965–3971. https://doi.org/10.1016/j.sjbs.2021.04.016
26. Bolan, S., Sharma, S., Mukherjee, S., Kumar, M., Rao, C. S., Nataraj, K. C., Singh, G., Vinu, A., Bhowmik, A., Sharma, H., El-Naggar, A., Chang, S. X., Hou, D., Rinklebe, J., Wang, H., Siddique, K. H. M., Abbott, L. K., Kirkham, M. B., & Bolan, N. (2024). Biochar modulating soil biological health: A review. *Science of The Total Environment*, *914*, 169585. https://doi.org/10.1016/j.scitotenv.2023.169585
27. Wijaya, I. M. W., Partama, I. G. Y., & Sumantra, I. K. (2023). Study on Nutrients Concentration Trends in Tukad Badung River Toward Nutrient Recovery Potential. *IOP Conference Series: Earth and Environmental Science*, *1268*(1), 012002. https://doi.org/10.1088/1755-1315/1268/1/012002
28. Ha, T.-H., Mahasti, N. N. N., Lu, M.-C., & Huang, Y.-H. (2023). Ammonium-nitrogen recovery as struvite from swine wastewater using various magnesium sources. *Separation and Purification Technology*, *308*, 122870. https://doi.org/10.1016/j.seppur.2022.122870
29. Hofmann, A. H., Liesegang, S. L., Keuter, V., Eticha, D., Steinmetz, H., & Katayama, V. T. (2024). Nutrient recovery from wastewater for hydroponic systems: A comparative analysis of fertilizer demand, recovery products, and supply potential of WWTPs. *Journal of Environmental Management*, *352*, 119960. https://doi.org/10.1016/j.jenvman.2023.119960
30. Panasiuk, O. (2010). *Phosphorus Removal and Recovery from Wastewater using Magnetite* [KTH Royal Institute of Technology, Sweden], [Accessed: July.13, 2025].
31. Silva, N. A., Glover, C. J., & Hiibel, S. R. (2023). Nutrient recovery by microalgae in aqueous product of hydrothermal carbonization of dairy manure. *Cleaner Waste Systems*, *6*, 100110. https://doi.org/10.1016/j.clwas.2023.100110
32. Gong, Y.-P., Ni, Z.-Y., Xiong, Z.-Z., Cheng, L.-H., & Xu, X.-H. (2017). Phosphate and ammonium adsorption of the modified biochar based on Phragmites australis after phytoremediation. *Environmental Science and Pollution Research*, *24*(9), 8326–8335. https://doi.org/10.1007/s11356-017-8499-2

33. Jiang, Y.-H., Li, A.-Y., Deng, H., Ye, C.-H., Wu, Y.-Q., Linmu, Y.-D., & Hang, H.-L. (2019). Characteristics of nitrogen and phosphorus adsorption by Mg-loaded biochar from different feedstocks. *Bioresource Technology*, *276*, 183–189. https://doi.org/10.1016/j.biortech.2018.12.079
34. Singh, V. K., Singh Gill, A. A., Singh, A., Singh, O., & Singh, T. (2022). Natural Potassium Fertilizers for Sustainable Agriculture. In *Encyclopedia of Green Materials* (pp. 1–13). Springer Nature Singapore. https://doi.org/10.1007/978-981-16-4921-9_262-1
35. Riseh, R. S., Vazvani, M. G., Hassanisaadi, M., & Thakur, V. K. (2024). Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries. *Industrial Crops and Products*, *208*(1), 117904. https://doi.org/10.1016/j.indcrop.2023.117904
36. Lavallais, C. M., & Dunn, J. B. (2023). Developing product level indicators to advance the nitrogen circular economy. *Resources, Conservation and Recycling*, *198*, 107167. https://doi.org/10.1016/j.resconrec.2023.107167
37. Chew, J., Joseph, S., Chen, G., Zhang, Y., Zhu, L., Liu, M., Taherymoosavi, S., Munroe, P., Mitchell, D. R. G., Pan, G., Li, L., Bian, R., & Fan, X. (2022). Biochar-based fertiliser enhances nutrient uptake and transport in rice seedlings. *Science of The Total Environment*, *826*, 154174. https://doi.org/10.1016/j.scitotenv.2022.154174
38. Rai, N., Ashiya, P., & Rathore, D. S. (2014). Comparative Study of the Effect of Chemical Fertilizers and Organic Fertilizers on Eisenia foetida. *International Journal of Innovative Research in Science, Engineering and Technology*, *3*(5).
39. Marcińczyk, M., Ok, Y. S., & Oleszczuk, P. (2022). From waste to fertilizer: Nutrient recovery from wastewater by pristine and engineered biochars. *Chemosphere*, *306*, 135310. https://doi.org/10.1016/j.chemosphere.2022.135310
40. Wijaya, I. (2025). Adsorption kinetics and isotherm study of ammonium and phosphate removal using magnesium-activated biochar. *Journal of Ecological Engineering*, *26*(6), 62–75. https://doi.org/10.12911/22998993/201996
41. APHA (American Public Health Association). (2017). *Standard Methods for The Examination of Water and Waste Water* (23rd ed.). American Water Works Association (AWWA) and Water Pollution Control Federation (WPCF), [Accessed: July.11, 2025].
42. Nafiah, R. (2016). Kinetics of Pb(II) Adsorption with Activated Charcoal Adsorbent from Siwalan Sabat (Kinetika Adsorpsi Pb (II) dengan Adsorben Arang Aktif Dari Sabut Siwalan). *Jurnal Farmasi Sains Dan Praktis*, *1*(2). https://doi.org/10.31603/pharmacy.v1i2.227
43. Nurhidayati, I., Mellisani, B., Puspita, F., & Rahmawati Putri, F. A. (2022). Determination of Isotherms and Kinetics of Iron Ion Adsorption by Sediment as Adsorbent (Penentuan Isoterm dan Kinetika Adsorpsi Ion Besi oleh Sedimen Sebagai Adsorben). *WARTA AKAB*, *46*(1). https://doi.org/10.55075/wa.v46i1.98
44. Gonçalves, F. A. R., Castro, G. F. de, Tronto, J., & Novais, R. F. (2022). Ionic adsorption and characterization of biochar from discarded potatoes. *Bragantia*, *81*. https://doi.org/10.1590/1678-4499.20210313
45. Wijayanti, I. E., & Kurniawati, E. A. (2019). Study of Adsorption Kinetics Isotherms Langmuir and Freundlich Equations on Scouring Powder as Adsorbents (Studi Kinetika Adsorpsi Isoterm Persamaan Langmuir dan Freundlich pada Abu Gosok sebagai Adsorben). *EduChemia (Jurnal Kimia Dan Pendidikan)*, *4*(2), 175. https://doi.org/10.30870/educhemia.v4i2.6119
46. Zhao, Z., Wang, B., Feng, Q., Chen, M., Zhang, X., & Zhao, R. (2023). Recovery of nitrogen and phosphorus in wastewater by red mud-modified biochar and its potential application. *Science of The Total Environment*, *860*, 160289. https://doi.org/10.1016/j.scitotenv.2022.160289
47. Agusriyadin, A. (2020). Characterization, Kinetics, and Isotherms of Coconut Waste Adsorption as a Cu(II) Ion Adsorbent (Karekterisasi, Kinetika, dan Isoterm Adsorpsi Limbah Ampas Kelapa sebagai Adsorben Ion Cu(II)). *SAINTIFIK*, *6*(2), 104–115. https://doi.org/10.31605/saintifik.v6i2.265
48. Setyorini, D., Arninda, A., Syafaatullah, A. Q., & Panjaitan, R. (2023). Determination of Freundlich Isotherm Constants and Adsorption Kinetics of Activated Carbon Against Acetic Acid (Penentuan Konstanta Isoterm Freundlich dan Kinetika Adsorpsi Karbon Aktif Terhadap Asam Asetat). *Eksergi*, *20*(3), 149. https://doi.org/10.31315/e.v20i3.10835

49. Phuong Tran, T. C., Nguyen, T. P., Nguyen, T. T., Le, P. C., Tran, Q. B., & Nguyen, X. C. (2022). Equilibrium single and co-adsorption of nutrients from aqueous solution onto aluminium-modified biochar. *Case Studies in Chemical and Environmental Engineering*, *5*, 100181. https://doi.org/10.1016/j.cscee.2022.100181
50. Andreas, A. (2015). Synthesis of Activated Carbon from Salak Peel Chemical Activation of KOH Compounds as Adsorbents in the Adsorption Process of Methylene Blue Dye (Sintesis Karbon Aktif dari Kulit Salak Aktivasi Kimia-Senyawa KOH sebagai Adsorben Proses Adosprsi Zat Warna . *Prosiding Seminar Nasional Teknik Kimia "Kejuangan,"* 1–7. https://jurnal.upnyk.ac.id/index.php/kejuangan/article/view/427
51. Krishna Murthy, T. P., Gowrishankar, B. S., Krishna, R. H., Chandraprabha, M. N., & Mathew, B. B. (2020). Magnetic modification of coffee husk hydrochar for adsorptive removal of methylene blue: Isotherms, kinetics and thermodynamic studies. *Environmental Chemistry and Ecotoxicology*, *2*, 205–212. https://doi.org/10.1016/j.enceco.2020.10.002
52. Addai, P., Mensah, A. K., Sekyi-Annan, E., & Adjei, E. O. (2023). Biochar, compost and/or NPK fertilizer affect the uptake of potentially toxic elements and promote the yield of lettuce grown in an abandoned gold mine tailing. *Journal of Trace Elements and Minerals*, *4*, 100066. https://doi.org/10.1016/j.jtemin.2023.100066
53. Bolan, S., Hou, D., Wang, L., Hale, L., Egamberdieva, D., Tammeorg, P., Li, R., Wang, B., Xu, J., Wang, T., Sun, H., Padhye, L. P., Wang, H., Siddique, K. H. M., Rinklebe, J., Kirkham, M. B., & Bolan, N. (2023). The potential of biochar as a microbial carrier for agricultural and environmental applications. *Science of The Total Environment*, *886*, 163968. https://doi.org/10.1016/j.scitotenv.2023.163968
54. Ren, T., Fan, P., Zuo, W., Liao, Z., Wang, F., Wei, Y., Cai, X., & Liu, G. (2023). Biochar-based fertilizer under drip irrigation: More conducive to improving soil carbon pool and promoting nitrogen utilization. *Ecological Indicators*, *154*, 110583. https://doi.org/10.1016/j.ecolind.2023.110583
55. Zeng, Z., Zhang, S., Li, T., Zhao, F., He, Z., Zhao, H., Yang, X., Wang, H., Zhao, J., & Rafiq, M. T. (2013). Sorption of ammonium and phosphate from aqueous solution by biochar derived from phytoremediation plants. *Journal of Zhejiang University SCIENCE B*, *14*(12), 1152–1161. https://doi.org/10.1631/jzus.B1300102
56. Zhang, M., Song, G., Gelardi, D. L., Huang, L., Khan, E., Mašek, O., Parikh, S. J., & Ok, Y. S. (2020). Evaluating biochar and its modifications for the removal of ammonium, nitrate, and phosphate in water. *Water Research*, *186*, 116303. https://doi.org/10.1016/j.watres.2020.116303
57. Abdelghany, A. E., Dou, Z., Alashram, M. G., Eltohamy, K. M., Elrys, A. S., Liu, X., Wu, Y., Cheng, M., Fan, J., & Zhang, F. (2023). The joint application of biochar and nitrogen enhances fruit yield, quality and water-nitrogen productivity of water-stressed greenhouse tomato under drip fertigation. *Agricultural Water Management*, *290*, 108605. https://doi.org/10.1016/j.agwat.2023.108605
58. Phares, C. A., Amoakwah, E., Danquah, A., Afrifa, A., Beyaw, L. R., & Frimpong, K. A. (2022). Biochar and NPK fertilizer co-applied with plant growth promoting bacteria (PGPB) enhanced maize grain yield and nutrient use efficiency of inorganic fertilizer. *Journal of Agriculture and Food Research*, *10*, 100434. https://doi.org/10.1016/j.jafr.2022.100434

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