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Effect of Chemical Activation on the Phosphate Adsorption Efficiency of Moringa oleifera Seed-Derived Activated Carbon in Wastewater Treatment

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Abstract

Introduction: Domestic wastewater contains phosphates originating from detergents, which are recognized as pollutants of aquatic and terrestrial environments. Excessive phosphate concentrations contribute to eutrophication, impairing ecosystem health. Adsorption using activated carbon has been identified as an effective method for phosphate removal. This study investigated the efficiency of activated carbon derived from Moringa oleifera seeds in removing phosphate from wastewater.

Methods: The study employed a pre- and post-test design with a control group. The carbon was activated using sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), and sodium chloride (NaCl) at concentrations of 5%, 10%, and 15%, with an activation duration of 24 hours. Phosphate concentrations were quantified at a wavelength of 880 nm using a UV-Vis spectrophotometer. Data were analyzed using SPSS and Microsoft Excel, incorporating normality tests and one-way analysis of variance (ANOVA).

Results: The activated carbon demonstrated phosphate removal efficiencies ranging from 73.55% to 79.21%, with the highest efficiency recorded for the G15 treatment (15% NaCl activation). The NaCl-activated carbon exhibited the greatest adsorption capacity, averaging 9.98×10^{-3} mg/g. Normality testing confirmed that the data were normally distributed, while ANOVA revealed that the interaction between activator type and concentration significantly affected the final phosphate concentration ($P = 0.001$; $P < 0.05$).

Conclusion: Activation with NaCl enhanced the stability of the carbon structure, likely facilitated by active compounds such as *Rhamnosyloxy benzyl isothiocyanate* (RBITC) in *Moringa* seeds. Optimization of activator concentration and field-scale validation are recommended to improve the applicability of *Moringa*-based activated carbon as a sustainable phosphate adsorbent.

Keywords: Charcoal, Moringa oleifera, Phosphates, Wastewater

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Introduction

Wastewater, as a byproduct of human activities, exerts significant impacts on the environment, especially on aquatic ecosystems. Effective treatment of this waste requires tailored approaches that consider factors such as volume, concentration, and its specific characteristics. These impacts predominantly arise from various anthropogenic sources, including both large-scale and small-to-medium industrial operations. The effectiveness of waste management depends on the systematic implementation of reduction, treatment, and reuse processes (1).

Domestic wastewater is generally recognized as a principal contributor to environmental wastewater pollution. A study conducted at Lake Burullus in Egypt identified domestic wastewater as the predominant source of organic pollution, responsible for approximately 63.2% of the total organic pollutant load, while industrial wastewater accounted for a comparatively smaller proportion (2). A large part of domestic wastewater contains phosphate, which mostly comes from detergents used in household tasks like doing laundry and washing kitchen utensils (3). Large amounts of phosphate can pollute water and soil if it is not treated properly. In water environments, high phosphate levels can cause eutrophication, which means high algae growth. This can upset the balance of the ecosystem, lower oxygen levels in the water, and harm aquatic life (4). The build-up of phosphate in soil can disturb the balance of nutrients and may also pollute groundwater. In addition, chemical fumes from phosphate-based detergents can pollute the air and create unpleasant smells. Because of this, reducing and treating phosphate in domestic wastewater is very important for protecting the environment. Some wastewater treatment methods can reduce phosphate levels by up to 80%, helping to reduce the harm to aquatic ecosystems (5).

Phosphate in domestic wastewater mostly comes from detergents. These detergents are widely used in homes and industries, especially for cleaning clothes and utensils (6). Commercial detergents contain phosphate compounds like sodium tripolyphosphate (STPP), which help soften water and improve cleaning power. However, STPP is hard to break down, and it can cause phosphorus to build up in water (7). This process can lower the amount of dissolved oxygen in the water and disturb the balance of aquatic ecosystems. Because of this, the use of STPP should be controlled and replaced with more eco-friendly alternatives to reduce its negative impact on water quality and the environment (5).

In Indonesia, the use of detergents has increased along with population growth and household needs (8). As a result, household wastewater with detergents has become a major source of phosphate pollution in water (5). Detergents that contain phosphate are a key cause of phosphate pollution in household water systems (9).

One way to reduce phosphate in wastewater is using adsorption with activated carbon. Activated carbon is known to be an effective adsorbent because it has a large surface area, many pores, and active groups that can bind with phosphate ions. However, since commercial raw materials are often expensive and limited, researchers are looking for cheaper and more sustainable sources. Moringa oleifera seeds have shown promise as one of these alternative sources.

Moringa seeds are considered a good material for making carbon. They contain high levels of organic carbon and fiber, with a carbon content of 46.78% (10). In addition, they are a common agricultural byproduct that is not yet fully used or taken advantage of (11). In addition, the bioactive compounds present in Moringa oleifera seeds may contribute to the formation of a stable activated carbon structure, thereby enhancing its effectiveness as an adsorbent (12).

To improve the phosphate adsorption ability of activated carbon made from Moringa seeds, it needs to go through an activation process. This can be done using physical or chemical methods to increase the pore surface area and add more functional groups. Previous studies have demonstrated the potential of *Moringa oleifera* seeds as natural adsorbents for various contaminants in wastewater, including turbidity and color from synthetic dairy effluent, chlorpyrifos, red dye, and direct dye (13–16). While these findings confirm their versatility, most research has focused on single adsorbent forms or specific activation methods. Many studies have shown that proper activation, combined with optimal dosing and adsorbent selection tailored to the physicochemical properties of target pollutants, can substantially enhance adsorption efficiency. Building on this premise, the present study assessed the effects of three chemical activators (H_2SO_4, NaOH, NaCl) at different concentrations on phosphate removal using furnace-activated *M. oleifera* seed carbon.

This study aimed to find out how different types and amounts of activators affect the ability of Moringa seed carbon (activated using a furnace) to reduce phosphate levels.

Materials and Methods

This study employed an experimental design with a pre- and post-test model and a control group to evaluate the efficacy of chemically activated carbon derived from Moringa oleifera seeds in removing phosphate from laundry wastewater. Three chemical activators were used: sulfuric acid (H_2SO_4) as an acid activator, sodium hydroxide (NaOH) as a base activator, and sodium chloride (NaCl) as a salt activator, each applied at concentrations of 5%, 10%, and 15%.

Carbonization process

Dried Moringa seeds were carbonized at 400°C for 45 minutes, then ground and sieved. This temperature was chosen to avoid excessive ash formation, which can block pores and reduce activated carbon effectiveness (17).

Activation process

Carbonized Moringa seed charcoal was mixed with the activator solutions at a weight-to-volume ratio of 1:10 (w/v) and incubated for 24 hours (18). After activation, the samples were dried in an oven at 105°C for 1 hour, then washed repeatedly with distilled water until the wash water reached neutral pH (12).

Adsorption procedure

Each adsorption experiment used 1 g of activated carbon with a carbon-to-wastewater mass-to-volume ratio of 1:10 (g/mL). The adsorption process was conducted at room temperature for 24 hours. The laundry wastewater, sourced from household laundry activities, contained detergent residues. Before adsorption, the wastewater underwent wet digestion with nitric acid (HNO_3) to break down complex organic compounds.

Phosphate measurement and analysis

Phosphate concentrations were measured using a UV-Vis spectrophotometer at a wavelength of 880 nm. Measurements were taken on filtrates obtained after contact with activated carbon, as well as on untreated wastewater samples used as controls. Activated carbon samples were weighed using an analytical balance, placed in labeled glass bottles, mixed thoroughly with wastewater, and allowed to interact for 24 hours. Post-adsorption, the carbon was separated by filtration, and the filtrate was collected for phosphate analysis in the laboratory.

Experimental design and data analysis

A Completely Randomized Design (CRD) was implemented to minimize experimental variability and improve the accuracy of the results. Data collected from pre- and post-treatment phases were analyzed using Microsoft Excel and

SPSS software.

Effectiveness analysis

The adsorption effectiveness was evaluated by measuring the ability of activated carbon to reduce phosphate levels in laundry wastewater. Phosphate concentrations were measured using spectrophotometry, and removal efficiency was calculated by:

$$Effectiveness = \frac{C_0 - C}{C_0} \times 100\%$$

Where C_0 is the initial phosphate concentration and C is the phosphate concentration after treatment.

Adsorption capacity

Adsorption capacity (q_e) represents the maximum amount of adsorbate that can attach to the adsorbent surface per unit mass once the system reaches equilibrium, which occurs when the rates of adsorption and desorption are equal (19). The adsorption capacity was calculated using the following formula:

$$q_e = \frac{(C_0 - C) \times V}{m}$$

Where q_e is the adsorption capacity (mg/g), C_0 is the initial adsorbate concentration (mg/L), C is the equilibrium adsorbate concentration (mg/L), V is the volume of solution (L), and m is the mass of adsorbent (g).

Results

Figure 1 illustrates how phosphate levels decreased when treated with Moringa seed activated carbon across nine different treatments: Treatment A, B, and G, each tested at concentrations of 5%, 10%, and 15%. Phosphate measurements were taken in triplicate using UV spectrophotometry, and the average values for each replicate were calculated for every treatment.

Figure 1 shows that the phosphate adsorption efficiency of Moringa seed activated carbon varied depending on the chemical activator used. Activation with H_2SO_4 (Treatment A) achieved efficiencies between 73.93% and 76.52%, averaging 75.47%. NaOH activation (Treatment B) had a similar range of 73.55% to 76.43%, averaging 75.41%. Meanwhile, NaCl activation (Treatment G) ranged from 72.68% to 79.21%, with an average efficiency of 75.66%. Notably, the G15 treatment recorded the highest efficiency at 79.21%, suggesting that NaCl activation offers the greatest potential for phosphate adsorption. These results were calculated based on the initial phosphate concentration of 0.2593 mg/L, which served as the untreated wastewater control.

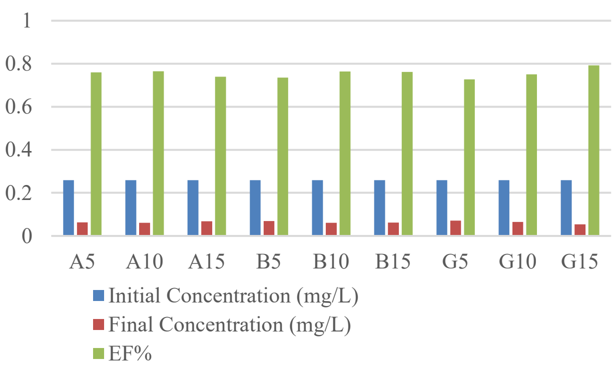

Figure 1. Phosphate Adsorption Efficiency

The adsorption capacity of Moringa seed carbon was measured after 24 hours of treatment contact.

As shown in Table 1, Treatment A demonstrated adsorption capacities ranging from 9.35 to 10×10^{-3} mg/g, with an average of 9.77×10^{-3} mg/g. Treatment B ranged slightly higher, from 9.40 to 10.10×10^{-3} mg/g, averaging 9.78×10^{-3} mg/g. Meanwhile, Treatment G showed the widest range, from 8.90 to 10.42×10^{-3} mg/g, and recorded the highest average adsorption capacity of 9.98×10^{-3} mg/g.

According to the findings presented in Table 2, the results of the normality test indicated that the data were normally distributed. This is demonstrated by P-values greater than 0.05 for each of the variables that were tested.

As shown in Table 3, the results of analysis of variance (ANOVA) indicate that neither the type of activator ($P = 0.893$) nor its concentration ($P = 0.415$) had a significant effect on the final phosphate concentration, as both P-values exceeded 0.05. However, the interaction between the type and concentration of the activator exhibited a significant effect on the final phosphate concentration ($P = 0.001$; $P < 0.05$).

A portion of the documentation from the research process is presented in Figure 2.

Discussion

Figure 1 shows that the effectiveness of Moringa seed

Table 1. Adsorption Capacity of Activated Carbon

No.	Treatment	Kapasitas Adsorpsi ($\times 10^{-3}$ mg/g)
1	1st Replication of Treatment A5	10
2	2nd Replication of Treatment A5	9.65
3	1st Replication of Treatment A10	10
4	2nd Replication of Treatment A10	9.80
5	1st Replication of Treatment A15	9.82
6	2nd Replication of Treatment A15	9.35
7	1st Replication of Treatment B5	9.40
8	2nd Replication of Treatment B5	9.67
9	1st Replication of Treatment B10	10.10
10	2nd Replication of Treatment B10	9.75
11	1st Replication of Treatment B15	9.85
12	2nd Replication of Treatment B15	9.92
13	1st Replication of Treatment G5	8.90
14	2nd Replication of Treatment G5	9.95
15	1st Replication of Treatment G10	9.92
16	2nd Replication of Treatment G10	9.55
17	1st Replication of Treatment G15	10.12
18	2nd Replication of Treatment G15	10.42

Table 2. Results of the data normality test

No.	Treatment Description	*P*-value
1	The final phosphate concentration of treatment A5	0.420
2	The final phosphate concentration of treatment A10	0.115
3	The final phosphate concentration of treatment A15	0.233
4	The final phosphate concentration of treatment B5	0.086
5	The final phosphate concentration of treatment B10	0.062
6	The final phosphate concentration of treatment B15	0.972
7	The final phosphate concentration of treatment G5	0.058
8	The final phosphate concentration of treatment G10	0.332
9	The final phosphate concentration of treatment G15	0.689

Figure 2. A portion of the documentation from the research process

activated carbon in adsorbing phosphate is strongly influenced by both the type and concentration of the chemical activator used during activation. It has been demonstrated that strong acid-based (H_2SO_4) and strong base-based (NaOH) activators have a tendency to reduce the effectiveness of adsorption when employed at high concentrations. This reduction is likely due to damage to the carbon's pore structure. Activation with H_2SO_4 tends to cause strong dehydration reactions, which increases rigidity in the carbon framework (20). On the other hand, activation with NaOH can cause excessive dissolution of the carbon surface, which may damage the micropores (21).

Additionally, excess ions from activation using strong acids or bases can create steric hindrance, making it harder for phosphate to penetrate the pores of the activated carbon (22). This phenomenon can form a barrier layer on the adsorbent surface, hindering diffusion (23). These findings imply that under conditions of ionic imbalance, adsorption efficiency undergoes a substantial decline (24,25).

In contrast, activation with NaCl shows a positive trend, where higher concentrations steadily improve phosphate adsorption efficiency. The study found that NaCl activation yielded the highest adsorption capacity, with an average of 9.81×10^{-3} mg/g, and the highest phosphate removal efficiency of 75.66%. Based on Table 2, the G15 treatment demonstrated the highest efficiency, reaching 80.37%, and exhibited an adsorption capacity of 10.42×10^{-3} mg/g. This benefit comes from the way NaCl activates the carbon—rather than damaging its structure, it helps open and clean the pores by removing tar and carbonization residues, while also increasing the number of active pores (26,27).

Table 3. Result of ANOVA Test

No.	Treatment	*P*-value
1	Activator Type	0.893
2	Activator Concentration	0.415
3	Type * Concentration	0.001

NaCl also functions as a mild and effective dehydrating agent, which does not cause hardening but instead enhances the interaction space between adsorbent and adsorbate through van der Waals forces (28). In addition, activation with NaCl does not require complex chemical reactions. It also helps reduce the moisture in the carbon, which in turn increases the number of active pores (29–31). The ability of Moringa seed activated carbon to remove phosphate is also supported by the presence of a compound called Rhamnosyloxy benzyl isothiocyanate (RBITC). This compound has a positive charge and a strong attraction to phosphate ions (32). The activation process makes the carbon more effective by increasing its surface area and adding more functional groups (33).

The effectiveness of the activated carbon depends on the type and concentration of the activator used during the activation process. This matches the results from the ANOVA test in Table 3, indicating that these two factors have a significant effect. In this study, NaCl gave better results than NaOH and H_2SO_4, based on the properties of the filtrate. The filtrate produced during activation can be an early sign of how well the activator reacts with the carbon structure. Activation with NaOH and H_2SO_4 resulted in a dark and dense filtrate, indicating excessive reactions (i.e., overreaction). A significant portion of the organic compounds from the carbon precursor dissolved into the activator solution. Such overreaction has been demonstrated to cause damage or dissolution of the carbon pore structure, thereby reducing its adsorption capacity (21). This phenomenon can be attributed to the corrosive and reactive nature of NaOH (a strong base) and H_2SO_4 (a strong acid). These substances have the capacity to dissolve not only impurities present in the carbon material but also significant structural components, such as lignin, cellulose, and hemicellulose.

Treatment with NaOH, especially at higher concentrations (up to 60%) and pretreatment temperatures around 170°C, has been found to remove up to 97.3% of hemicellulose and 45% of lignin from biomass (34). Indeed, the extent of lignin removal has been shown to reach 58.6–75.3%, contingent upon the type of biomass utilized (35). Furthermore, the majority of hemicellulose is known to dissolve during treatment with NaOH/urea, while the crystalline structure of cellulose has been observed to transform from form I to form II, suggesting structural modification of the cellulose.

In contrast, using a NaCl solution produces a noticeably clearer filtrate, indicating a more controlled activation process that avoids excessive dissolution of the carbon material. As a neutral salt, NaCl is less corrosive than strong acids or bases. As a result, NaCl activation helps preserve the carbon's structure, allowing pores to form without causing significant damage to the active surface (36,37).

The clearer filtrate seen during the NaCl activation process suggests that fewer substances dissolved from the carbon material. This indicates effective impurity removal without damaging the core carbon structure. Activated carbon produced with NaCl shows efficient pore formation and an optimal surface area-to-burn-off ratio, reflecting a selective and gentle activation process (38). This outcome suggests that the activated carbon's effectiveness is enhanced due to the preservation of its microporous structure and high surface area.

The physical form of the activated carbon after activation varied noticeably depending on the type of activator used. Carbon treated with NaOH and NaCl tended to retain a fine granular texture both before and after neutralization, showing little change in shape. In contrast, carbon activated with H_2SO_4 appeared clumped and slightly sticky as shown in Figure 2. This occurred due to a significant drop in pH during activation, resulting in highly acidic carbon. The low pH affects how the carbon particles interact, making them more likely to stick together (39). This process also leads to the decomposition of organic compounds on the surface of the activated carbon, forming residual substances that accelerate the aggregation of carbon particles (40). This clumping is disadvantageous because it lowers the specific surface area, which is crucial for effective adsorption.

This study shows that chemically activated carbon derived from Moringa oleifera seeds effectively enhances phosphate adsorption, with the type of activator influencing the physical, chemical, and adsorption properties of the carbon. Industrial wastewater can also be processed and utilized as liquid organic fertilizer to increase agricultural productivity, such as the treatment of wastewater from the WWTP of PT X, which has a significant effect on the growth of *Brassica rapa L.* (41). At a larger scale, this method can be combined with the use of sludge from wastewater treatment. If the sludge meets safety standards and contains beneficial nutrients, it can be directly applied as fertilizer (42). Additionally, sludge can be co-composted with other organic wastes to produce high-quality compost that is safe for agricultural use (43).

By integrating these two approaches- carbon activation from Moringa biomass and sludge co-composting- the value of waste materials can be significantly enhanced. Activated carbon serves as an effective adsorbent for wastewater treatment, while co-composted sludge contributes to improving soil quality. This integrated approach supports sustainable waste management while increasing agricultural productivity and resource use efficiency.

Conclusion

The key finding of this study is that the type of chemical activator greatly influences the phosphate adsorption efficiency of activated carbon made from Moringa oleifera seeds. Activation with NaCl proved to be the most effective, achieving a peak adsorption of 79.21% in the G15 treatment and an average efficiency of 75.66%. Meanwhile, the activators H_2SO_4 and NaOH showed almost similar average efficiencies of 75.47% and 75.41%, respectively. In addition, the adsorption capacity of the activated carbon followed a similar trend, with NaCl exhibiting the highest capacity of 9.98×10^{-3} mg/g, followed by NaOH (9.78×10^{-3} mg/g) and H_2SO_4 (9.77×10^{-3} mg/g), respectively.

The activation process was visually monitored, and the observations support the earlier findings. Activation with NaCl produced a clearer filtrate and finer carbon deposits, indicating a more controlled reaction. In contrast, using NaOH and H_2SO_4 resulted in thicker, more viscous filtrates and sticky, clumped carbon formations. These results suggest that the highly reactive nature of strong acids and bases can cause overreaction, which not only removes impurities but also breaks down important biomass components like lignin, cellulose, and hemicellulose.

The effectiveness of Moringa seed activated carbon in adsorbing phosphate is further supported by the active compound Rhamnosyloxy benzyl isothiocyanate (RBITC). This compound carries an electropositive charge, giving it a strong attraction to phosphate anions. As a result, RBITC enhances the ionic interactions between the carbon surface and phosphate ions in the wastewater, boosting the overall adsorption process.

This study highlights the promising potential of Moringa seed activated carbon as an eco-friendly, natural adsorbent—especially when activated with NaCl. This method not only efficiently removes phosphate but also preserves the carbon's structural integrity. These findings provide a solid foundation for developing sustainable adsorption techniques to treat laundry wastewater. Future research should focus on optimizing activator concentrations, scaling up carbon production, and evaluating its performance in real wastewater conditions. Moreover, gaining a deeper understanding of the chemical and structural changes that occur during activation is essential for improving adsorption performance. Combining these insights could pave the way for developing more efficient and sustainable solutions for managing phosphate waste in the future.

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Competing Interests
None.

Ethical Approval
Does not require any ethical issues.

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