Ammonium Adsorption from Water by Macadamia Husk-Derived Biochar Forms: Mechanism and Behavior Study

Phuong Van Nguyen*

Institute of Environmental Science, Engineering and Management, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao Street, Hanh Thong Ward, Ho Chi Minh City 700000, Vietnam

*** Corresponding author:**

email: nguyenvanphuong@iuh.edu.vn

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Abstract: *Ammonium (NH_4^+) is a nutrient and a pollutant of the aquatic environment. This study aims to evaluate the ability to recover NH_4^+ in water through the adsorption studies of macadamia husk-derived biochar at different pyrolysis temperatures (300, 450, and 600 °C). An experimental design was used to investigate adsorption conditions, including pH, biochar dosage, and NH_4^+ concentration in water, by letting biochar contact with NH_4^+ solution for about 2 h. Kinetic studies were also considered at different times. The results showed that the optimal parameters included pH 4, biochar dosage of 10 g L^{-1}, and initial NH_4^+ concentration for saturated adsorption of 166.7 mg L^{-1}. The highest NH_4^+ adsorption capacity of the three biochar forms ranged from 16.4 to 18.2 mg g^{-1}, and the equilibrium time was 15–30 min. The Freundlich model is suitable for explaining the process behavior. Meanwhile, the pseudo-second-order kinetic model describes the mechanism of NH_4^+ adsorption process. The study provided a solution to utilize agricultural waste as an NH_4^+ adsorbent, as this adsorbed material can be used as fertilizer.*

Keywords: *NH_4^+ adsorption; biochar; equilibrium; kinetics; macadamia husk*

■ INTRODUCTION

Ammonium (NH_4^+) is a key constituent of total nitrogen in domestic wastewater, particularly livestock wastewater. The discharge of excessive NH_4^+ into water bodies leads to significant environmental pollution [1-3]. Therefore, it is necessary to control and remove NH_4^+ from water effectively. Ion exchange, adsorption, chemical precipitation, biological treatment, and physicochemical treatment are commonly used to remove NH_4^+ from water [2,4]. Among them, the exchange and adsorption processes have attracted much attention from scientists. Adsorbents/exchanges such as activated carbon, clay minerals, carbon nanotubes, and graphene have high NH_4^+ adsorption capacity. Still, their cost is higher than the use of biochar produced from agricultural by-products [2,5]. Specifically, many studies have used these forms of biochar as adsorbent materials, showing high efficiency, low cost, and environmental friendliness [1-2,6]. Furthermore, after the adsorption process, biochar can finally be converted into useful fertilizer products [7].

Macadamia is widely grown in Dak Nong, Vietnam, with about 1100 ha, yielding 1.5 tons of nuts/ha, and waste husks accounting for 75%. Macadamia husks are often used as garden mulch or compost, but their poor decomposition ability makes them inefficient. Therefore, research and development of a material to adsorb NH_4^+ from water using biochar derived from macadamia husks is worth considering. Fidel et al.'s study [8] on the fluctuation of NH_4^+ adsorption capacity when changing pyrolysis temperature did not always follow a clear trend. Meanwhile, the biochar surface area did not determine the NH_4^+ adsorption capacity from water [1,9].

The physical properties of the biochar surface are not the leading cause affecting the ability to remove NH_4^+ from water but are related to the acidic functional groups on the biochar surface [10-11]. The research conducted by Xu et al. [2] demonstrated that biochar produced at lower pyrolysis temperatures achieves the highest NH_4^+ adsorption efficiency from water, as supported by the oxygen-containing functional groups known from Fourier transform-infrared (FTIR) data of the biochar. However, the extent of this reduction is not clear [12]. Additionally, many studies have used biochar to adsorb NH_4^+ from water using different raw sources such as corn, red oak (*Quercus rubra*), maple, wheat [8], and coffee husks [12]. However, information on the use of waste sources from macadamia husks in Dak Nong, Vietnam, is still lacking. Therefore, an investigation of the adsorption capacity of biochar derived from macadamia husk for water at different preparation temperatures has been considered. Specific objectives are (i) to investigate the influencing factors and mechanism of NH_4^+ adsorption from water by biochars, and (ii) to determine the mechanism and behavior of NH_4^+ adsorption from water (kinetic and equilibrium studies). The study can provide a theoretical basis for the potential application of macadamia husk-derived biochar for NH_4^+ removal from water and agricultural resource utilization.

■ EXPERIMENTAL SECTION

Materials

Chemicals, including KCl, HCl, NaOH, HNO_3, NaOH, H_2SO_4 (China), $K_2Cr_2O_7$, Neteller indicator, EDTA, and NH_4Cl, purchased from Merck, were used in the study.

Instrumentation

Nabertherm P330 furnace (Germany) was used to prepare biochar. Ultraviolet-visible (UV-vis) spectroscopy Model GENESYS 10S, 6-/1-CELL, Thermo Scientific, USA was used for NH_4^+ analysis. Spectroscopy FTIR-4700 type A with 350–4,000 cm^{-1} resolution was used to determine the surface groups of biochar. DLAB DM 0636 sample separation centrifuge was used for solid/liquid separation after adsorption.

Procedure

Biochar preparation

The experimental design was based on previous research with slight modifications [1,12]. Specifically, macadamia husks were pyrolyzed in a furnace at 3 temperatures of 300, 450, 600 °C, heated at 10 °C/min, stored for 2 h, and cooled naturally in the furnace. Then the results are grounded, sieved 1 mm, and stored at 4 °C. Fig. 1 shows the raw materials and the produced biochar from macadamia husk. Some properties of the biochar, such as pH, pH_{pzc}, and surface functional groups, are presented in previous studies [13].

Adsorption effects pH and biochar dosage

To examine the effect of pH on biochar's adsorption with NH_4^+, 0.3 g of biochar (pyrolyzed at 300, 450, and 600 °C) was mixed with 30 mL of 0.01 M $CaCl_2$ solution (83 mg L^{-1} NH_4^+) in 60 mL polypropylene tubes at initial pH values of 2, 4, 6, and 8. The mixture was then stirred on a GFL 3015 (Germany) circular shaker at 350 rpm at a room temperature of 27 °C for 2 h. After equilibration, the solid and liquid phases were separated by centrifugation at 4,000 rpm for 15 min using a DLAB DM0636 centrifuge (USA) and filtered through a 0.22 µm filter. NH_4^+ was analyzed based on ISO 7150-1: 1984 E.

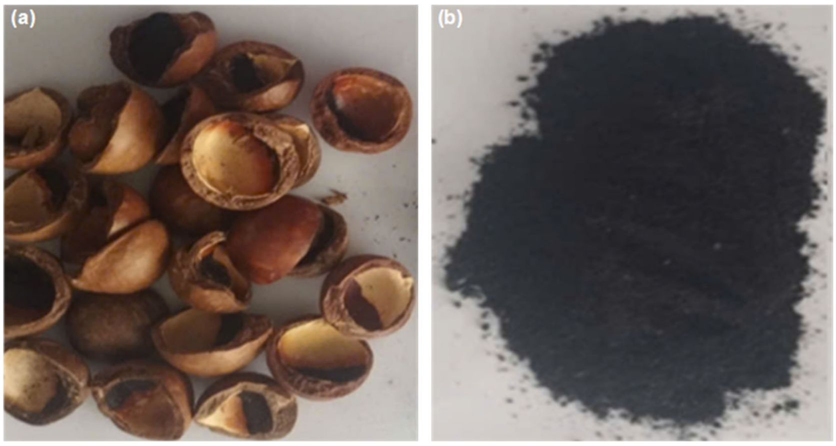

Fig 1. (a) Raw materials and (b) biochar from macadamia husk

The adsorption capacity and removal efficiency were calculated to select the pH for the biochar dosage experiment. The biochar dosage was determined with the selected pH in the previous experiment, and the same procedure was performed to determine the optimum biochar dosage in the survey series of 3.3, 10.0, 16.7, 23.3, and 33.3 g L^{-1}. Similarly, the pH and biochar dosage were selected for the subsequent experiments.

Behavioral and mechanistic study

The behavior of NH_4^+ adsorption process was determined based on the experimental conditions, such as pH and biochar dosage selected, along with the initial NH_4^+ concentration series of 0, 7, 17, 33, 67, 83, 167, and 333 mg L^{-1}. The process was carried out similarly to the previous experiments. The equilibrium adsorption isotherm, Langmuir, and the Freundlich parameters were used to evaluate the agreement between the experimental and calculated results from the model. The mechanism of NH_4^+ adsorption process was determined based on experiments examining NH_4^+ adsorption capacity at times of 0, 10, 15, 30, 45, 60, 90, and 120 min with conditions such as initial NH_4^+ concentration of 83 mg L^{-1}, pH, and selected biochar dosage. The process was conducted similarly to previous experiments. Pseudo-first-order and pseudo-second-order adsorption kinetic model parameters were used to evaluate the agreement with experimental results.

Experimental data analysis

The formula used to calculate the adsorption capacity (mg g^{-1}) is presented in Eq. (1);

$$q_i = \frac{(C_0 - C_i)\cdot V}{m} \qquad (1)$$

in which, C_0 and C_i (mg L^{-1}) are initial NH_4^+ concentration and at equilibrium time, V (L) is the volume of NH_4^+ solution, m (g) is the mass of adsorbent (biochar), and q_i (mg g^{-1}) is the NH_4^+ sorption capacity of sample i at equilibrium time. The NH_4^+ adsorption efficiency (%) is calculated using Eq. (2).

$$NH_4^+ \text{ adsorption efficiency}(\%) = \frac{C_0 - C_i}{C_0} \times 100\% \qquad (2)$$

Adsorption equilibrium based on the Langmuir isotherm model is expressed in Eq. (3) [12,14].

$$\frac{1}{q_i} = \frac{1}{K_L q_0}\frac{1}{C_i} + \frac{1}{q_0} \qquad (3)$$

The Langmuir sorption constant, denoted as K_L, is expressed in units of (L mg^{-1}). By plotting 1/q against 1/C and the form y = ax + b, q_0 can be determined, and the suitability of the sorption isotherm can be examined.

Freundlich isotherm equation is shown in Eq. (4), and the linear form is in Eq. (5) [12,14];

$$q = y/m = K_F C^{\frac{1}{n_F}} \qquad (4)$$

$$\log q_i = \frac{1}{n_F}\log C_i + \log K_F \qquad (5)$$

where n_F: Freundlich isotherm constant showing NH_4^+ adsorption intensity, K_F: Freundlich adsorption isotherm constant showing adsorption capacity, and C_i is the NH_4^+ ion concentration of sample i at equilibrium time (mg L^{-1}).

Pseudo-first-order adsorption kinetics equation is shown in Eq. (6), while pseudo-second-order adsorption kinetics equation is presented in Eq. (7) [2];

$$\ln(q_e - q_t) = -k_1 t + \ln q_e \qquad (6)$$

$$\frac{1}{q_t} = \frac{1}{t}\frac{1}{k_2 q_e^2} + \frac{1}{q_e} \qquad (7)$$

where q_e: NH_4^+ sorption capacity at equilibrium time (mg g^{-1}), and q_t at time t; k_1, and k_2 are rate constants; t (min): adsorption time.

Data processing

To identify factors significantly influencing the response variable, ANOVA analysis was conducted in SPSS 23.0, with a significance level set at $p < 0.05$. Post hoc comparisons were performed using Tukey's test when the significance (Sig) was greater than 0.05, and Tamhane's test was applied when Sig was less than 0.05.

■ RESULTS AND DISCUSSION

Factors Affecting the Adsorption Capacity of NH_4^+ from Water by Biochars

Effect of pH

The increased NH_4^+ sorption capacity, observed in Bio 300 (macadamia husk biochar pyrolyzed at 300 °C) as pH climbed from 2 to 6, was calculated using Eq. (1) and is presented in Fig. 2(a). Specifically, the NH_4^+ adsorption capacity increased significantly from 8.08 to

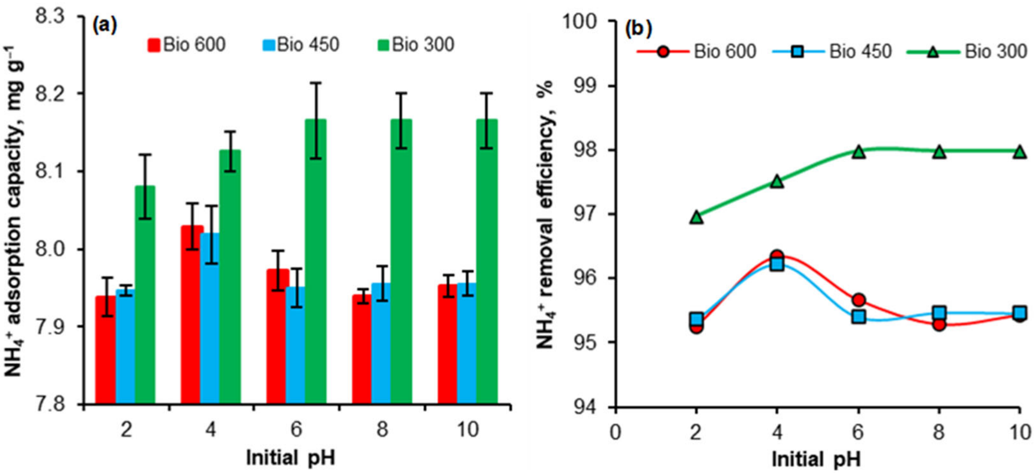

Fig 2. (a) NH_4^+ adsorption capacity and (b) removal efficiency of biochars at different pH

8.12 and then to 8.136 mg g^{-1} corresponding to the initial pH of 2, 4, 6. When the initial pH continued to increase to 10, the adsorption capacity increased insignificantly (according to ANOVA analysis). In the case of biochar 450 °C (Bio 450), Fig. 2(a) showed that when increasing pH from 2 to 4, the adsorption capacity increased statistically significantly; specifically, the sorption capacity increased from 7.95 to 8.02 mg g^{-1}. When pH increased to 6, NH_4^+ adsorption capacity decreased to 7.95 mg g^{-1}, and further increases in pH from 8 to 10 did not produce a statistically significant change, as determined by one-way ANOVA analysis with biochar pyrolyzed at 600 °C, based on Fig. 2(a), the results showed that when the initial pH increased from 2 to 10, the NH_4^+ adsorption capacity changed without statistical significance ranging from 7.94 to 8.03 mg g^{-1}.

The NH_4^+ adsorption efficiency of Bio 300 increased significantly from 97.0 to 97.9% as pH rose from 2 to 6, stabilizing thereafter. For Bio 450 (Fig. 2(b)), efficiency rose considerably from 95.4 to 96.2% between pH 2–4, then dropped to 95.4% at pH 6 and remained stable. Bio 600 showed a slight, insignificant increase (95.3–96.3%) across pH 2–10. pH thus exerted distinct effects on each material's performance.

All three biochars used for NH_4^+ removal in water showed optimal removal efficiency at pH 4, except for Bio 300, which maintained high removal capacity at pH values in the range of 6–10. The reason could be explained by the protonation and deprotonation of surface functional groups being affected by solution pH, and this significantly affected the bonding between oxygen-containing functional groups on the biochar surface and NH_4^+. This resulted in an impact on NH_4^+ adsorption by biochar [9]. Specifically, pH 2 (low pH) is unfavorable for adsorption, possibly due to too many H^+ ions competing for NH_4^+ adsorption sites on the biochar surface [2]. At this time, the NH_4^+ adsorption process in water occurs according to the ion exchange mechanism [1]. When pH is increased but < 8, most of the NH_4^+ is present in ionized form and will best support its removal. Xu et al. [2] also noted a corresponding explanation, stating that the pH is favorable for NH_4^+ adsorption. However, when pH was increased to 10, the removal capacity decreased or remained unchanged. This may be due to the ability of NH_4^+ ions to convert a small part to $NH_3·H_2O$, leading to a decrease in the ability to compete with NH_4^+ in water.

However, the evaluation of the removal efficiency of the three types of biochar did not fluctuate much under the condition of pH 4, biochar dosage of 10 g L^{-1}, and initial NH_4^+ concentration of 83 mg L^{-1}. A comparative assessment of adsorption capacity and removal efficiency determined the selection of pH 4 for subsequent testing.

Effect of biochar dosage

Fig. 3(a) visually illustrates the influence of biochar dosage on the NH_4^+ sorption capacity of Bio 300, conducted at pH 4.0 and an initial concentration of

83 mg L^{-1}. The results showed that when the dosage increased from 3.3 to 33.3 g L^{-1}, the adsorption capacity decreased significantly at each dosage level, respectively, 24.06, 8.02, 4.90, 3.15, and 2.40 mg NH_4^+ g^{-1}. In the case of Bio 450 and Bio 600 (Fig. 3(a)), the results were similar to those of Bio 300. Specifically, with Bio 450, the NH_4^+ adsorption capacity decreased from 24.14, 8.02, 4.89, 3.03, and 2.15 mg g^{-1}, respectively, while with Bio 600 it was 21.01, 8.03, 4.26, 3.02, and 2.12 mg g^{-1}, respectively. This can be explained by the fact that when the biochar dose is low, the amount of NH_4^+ in the solution is high, ensuring complete adsorption. Therefore, when the biochar dose still increases, the capacity decreases, possibly due to the collision between the biochar particles that have adsorbed NH_4^+, leading to the re-dissolution of the adsorbed NH_4^+. An analogous explanation is also found in the study of Qureshi et al. [15]. The results of the investigation of the dosage of biochar forms on the NH_4^+ removal efficiency are presented in Fig. 3(b). The results showed the NH_4^+ removal efficiency of Bio 300 ranged from 96.2–97.7%, Bio 450 was 84.1–96.3%, and Bio 600 was 84.1–96.2%. Considering the adsorption capacity and removal efficiency at pH 4, the initial C_0 83 mg L^{-1} was used, and the biochar dosage of the three selected biochar forms was 10 g L^{-1}.

Effect of initial NH_4^+ content

Fig. 4 presents the analysis of the effect of initial NH_4^+ content in water on the sorption capacity of biochar

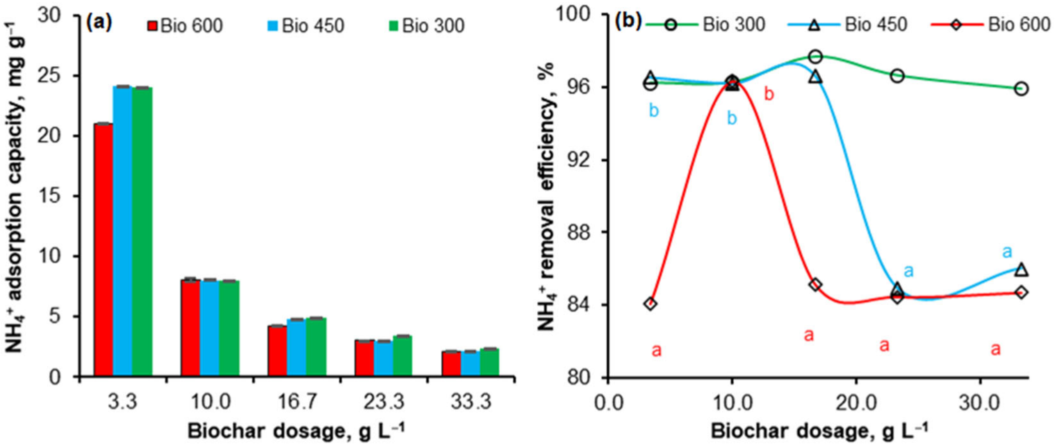

Fig 3. Effect of dosage on NH_4^+ (a) adsorption capacity and (b) removal efficiency, under experimental conditions such as pH 4, initial content of 83 mg L^{-1}

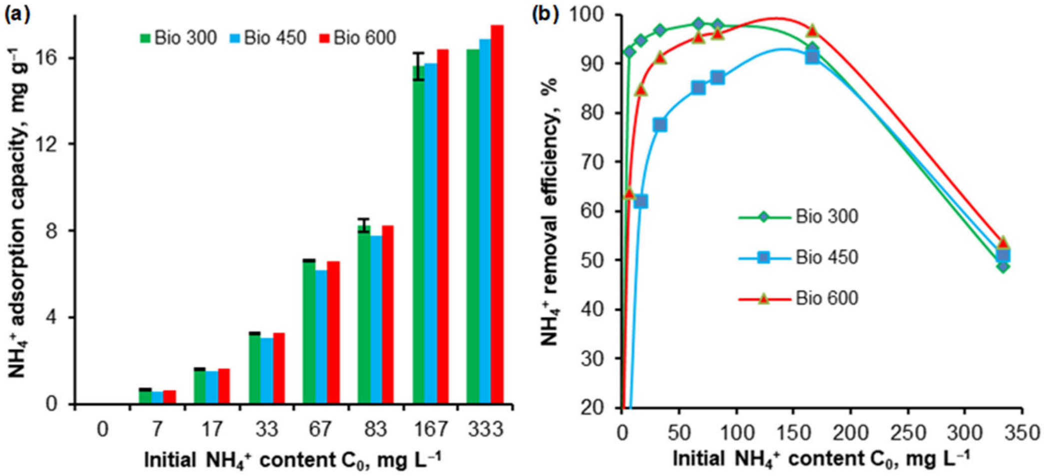

Fig 4. Effect of initial concentration on NH_4^+ (a) adsorption capacity and (b) removal efficiency, under controlled parameters: pH 4, biochar dosage of 10 g L^{-1}

forms. In the case of Bio 300, as shown in Fig. 4(a), the adsorption capacity increased statistically significantly by 1.7, 3.3, 6.6, 8.3, and 15.6 mg g^{-1} corresponding to the concentrations of 0.0, 16.7, 33.3, 66.7, 83.3, and 166.7 mg L^{-1}. Conversely, elevating the initial NH_4^+ concentration from 166.7 to 333.3 mg L^{-1} resulted in no substantial variation in adsorption capacity, suggesting the attainment of saturation. Analogously, for Bio 450 and Bio 600 (as shown in Fig. 3(a)), equilibrium saturation was reached at an initial NH_4^+ concentration of 333 mg L^{-1}.

At pH 4, the surface of all three types of biochar is positively charged ($pH < pH_{pzc}$, Table 1), so the NH_4^+ adsorption process is mainly due to the ion exchange mechanism [2]. Furthermore, oxygen-containing functional groups such as hydroxylic groups, carboxylic groups, and sulfonic acid groups on the biochar surface can also fix NH_4^+ ions by hydrogen bonding. In the saturated adsorption state, the NH_4^+ adsorption capacity of Bio 600 > Bio 450 > Bio 300 corresponds to 18.15, 17.5, and 16.4 mg g^{-1}. This may be due to the support of cations such as Na^+, Ca^{2+}, and Mg^{2+} on the biochar surface, replacing NH_4^+ in water, where the ion exchange mechanism occurs [16]. Furthermore, these cations on the biochar surface increased with increasing pyrolysis temperature [17]. The NH_4^+ adsorption capacity in our study was higher when compared with the study of Khalil et al. [1], which was 4.5 mg g^{-1} with biochar from rice husk, and that of Xu et al. [2], which was 7.09 mg g^{-1} with biochar derived from rice straw. The NH_4^+ removal efficiency from the water was high (80–96%), Fig. 4(b), when the initial NH_4^+ concentration ranged from 16.7–166.7 mg L^{-1}. Bio 300 gave the highest removal efficiency (98% at 66.7 mg L^{-1} content). The results of NH_4^+ removal ability were higher in the study of Khalil et al. (69.5% rice husk) [1].

The results of calculating the NH_4^+ adsorption equilibrium parameters in the water of 3 types of biochar, as presented in Table 1, showed that the Langmuir model is not suitable to explain the mechanism of the NH_4^+ adsorption process because the calculated results of the maximum NH_4^+ adsorption capacity (q_0) and the experimental adsorption value (q_{exp}) are very different. Meanwhile, the Freundlich model is more suitable, with R^2 ranging from 0.92–0.96, n_F, and K_F decreasing statistically significantly with increasing pyrolysis temperature. Both physical and chemical adsorption behaviors are implicated in the NH_4^+ adsorption process, as described by the Freundlich isotherm model for heterogeneous surfaces. However, because $n < 1$, the adsorption process is mainly chemical adsorption. Among them, the dominant processes are the ion exchange process and hydrogen bond formation between OH functional groups and NH_4^+ in water, as reported earlier [16]. In Table 1, q_{exp} is the adsorption capacity value obtained from the experimental results, and q_0 is calculated from the models.

NH_4^+ Adsorption Kinetics of Biochar

Kinetic data for NH_4^+ adsorption by three distinct biochars in water are displayed in Fig. 5(a). Specifically, Bio 300 exhibited a sharp, statistically significant increase in adsorption capacity during the initial 30 min, achieving 8.0 mg g^{-1}, followed by a slow, statistically insignificant progression to 8.1 mg g^{-1} by 45 min, where

Table 1. Adsorption equilibrium parameters

Model	Pyrolysis temperature (°C)	Parameters			
		q_0 (mg g^{-1})	K_L	R^2	q_{exp}
Langmuir model	300	−1.74	−0.59	0.97	16.4
	450	13.46	0.53	0.91	17.6
	600	−0.44	−0.31	0.98	18.1
		n_F	K_F	R^2	
Freundlich model	300	0.46^c	3.09^c	0.92	
	450	0.30^b	0.003^b	0.95	
	600	0.10^a	0.0001^a	0.96	

The letters a, b, and c represent statistically significant differences

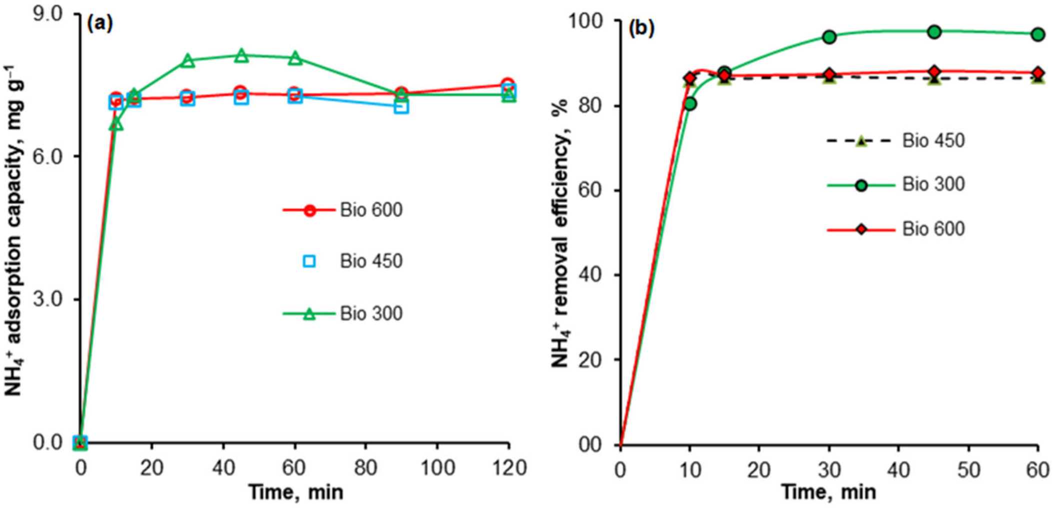

Fig 5. Effect of time on NH_4^+ (a) adsorption capacity and (b) removal efficiency, under experimental conditions such as pH 4, NH_4^+ concentration 83.3 mg L^{-1}, biochar dosage 10 g L^{-1}

equilibrium appeared to be reached. Similar to Bio 300, the NH_4^+ adsorption capacity of Bio 450 also increased rapidly (significantly increased) in the first 15 min, reaching an adsorption capacity of 7.2 mg g^{-1} and then increased slowly (increased without statistical significance) and seemed to stop at 30 min (reaching 8.2 mg g^{-1}). The results obtained from Bio 600 were similar to Bio 450, increasing rapidly in the first 15 min and stopping at 30 min. Research results were found on NaOH-modified rice husks, which showed that the adsorption rate was fast in the first 15 min and slow, and seemed to stop at 60 min [1]. The adsorption mechanism unfolded in two distinct phases. Stage 1, rapid uptake onto surface sites characterized by –OH and –COOH exchange centers. Stage 2, NH_4^+ diffuses slowly into the biochar, and the diffusion rate gradually decreases until reaching equilibrium. Thus, the NH_4^+ adsorption kinetics can be regulated by surface adsorption and diffusion within the particles [2,18].

The results of calculating the kinetic parameters of the NH_4^+ adsorption process of 3 types of biochar, as summarized Table 2, showed that the pseudo-first-order model is appropriate, with R^2 (0.87–0.96). However, the q_e value calculated from the model was completely different from the experimental value q_{exp}. Specifically, the calculated q_e for 3 types of biochar fluctuated from 0.17–2.8 mg g^{-1}, while the q_{exp} value fluctuated from 7.29–8.13 mg g^{-1}. Therefore, the pseudo-first-order model cannot explain the mechanism of the NH_4^+ sorption process on the studied biochars.

Meanwhile, with the pseudo-second-order kinetic model, the R^2 value was high at 0.99, and the calculated values of q_e and q_{exp} were approximately the same for three biochar types, as shown in Table 2. Therefore, this

Table 2. Parameters of NH_4^+ adsorption kinetic models

Models	Pyrolysis temperature (°C)	q_e (mg g^{-1})	Kinetic constant		q_{exp} (mg g^{-1})	R^2
Pseudo-first-order	300	2.80	k_1	0.073	8.13	0.96
	450	0.17		0.024	7.29	0.90
	600	0.33		0.009	7.50	0.87
Pseudo-second-order	300	8.74	k_2	0.038[a]	8.13	0.99
	450	7.25		1.116[b]	7.29	0.99
	600	7.27		1.215[b]	7.50	0.99

The letters a and b represent statistically significant differences. q_e is the maximum adsorption capacity calculated from the model, and q_{exp} is the adsorption capacity from the experiment adsorption model can be used to explain the sorption mechanism of NH_4^+ onto biochar derived from macadamia husks. This model was also chosen in the previous study of Xu et al. [2] when studying the NH_4^+ adsorption kinetics of clay/biochar mixtures. Furthermore, the constant k_2 showed an increasing trend with increasing pyrolysis temperature. Specifically, the k_2 of Bio 300 (0.038) was significantly different from that of Bio 450 (1.116) and Bio 600 (1.215). Meanwhile, the k_2 between Bio 450 and Bio 600 was not significantly different (One-way ANOVA analysis). Results of a kinetic study of NH_4^+ adsorption process in water by biochar derived from macadamia husks, with the contribution of surface chemical adsorption process, were similar to the previous study [1]. The NH_4^+ removal efficiency from water was high after 10 min of adsorption, ranging from 86–98%, Fig. 5(b), when the experimental conditions were pH 4, biochar dosage 10 g L^{-1}, and initial concentration 83.3 mg L^{-1}.

Fig. 6 showed that the peak at 3100–3500 cm^{-1} representing O–H bonds in biochar samples decreased (in the case of Bio 300) or disappeared (Bio 450 and Bio 600) when the adsorption process occurred, which proved that the –OH bonds participated in the adsorption process. The results also showed that the adsorption process could have shifted the O–H peak; the exchange bond with O–H···N–H interaction was thought to have caused this phenomenon. In addition, hydrogen bond adsorption with NH···N interaction was also observed according to the dipole rule [19]. Each of the three biochars exhibited absorption peaks around 3100 cm^{-1}, yet a shift in these peaks was noted post-adsorption, primarily due to the –OH stretching vibration associated with intermolecular hydrogen bonding. The participation of surface –OH groups in NH_4^+ ion adsorption, culminating in hydrogen bond formation, was evidenced by changes in transmittance spectra after adsorption, including decreased peak intensity, peak shifts, and peak broadening [20]. The absorption peaks mainly appeared at the wave numbers of 3000 and 1400 cm^{-1}, corresponding to the peaks of the stretching vibrations of –OH and COO^- groups on the biochar surface. Therefore, it can be said that the adsorption of NH_4^+ by biochar in the study may be due to the groups on the carbon surface forming coordination bonds and hydrogen bonds with nitrogen atoms [10].

■ CONCLUSION

Biochar derived from macadamia nut shells can be used as a NH_4^+ adsorbent. The adsorption capacity and removal efficiency of NH_4^+ in water are effective at pH 4. The optimal dosage is 10 g L^{-1}, and the adsorption process reaches saturation at the initial NH_4^+ content of 166.7 mg L^{-1}. The Freundlich isotherm model is appropriate for describing the NH_4^+ adsorption behavior

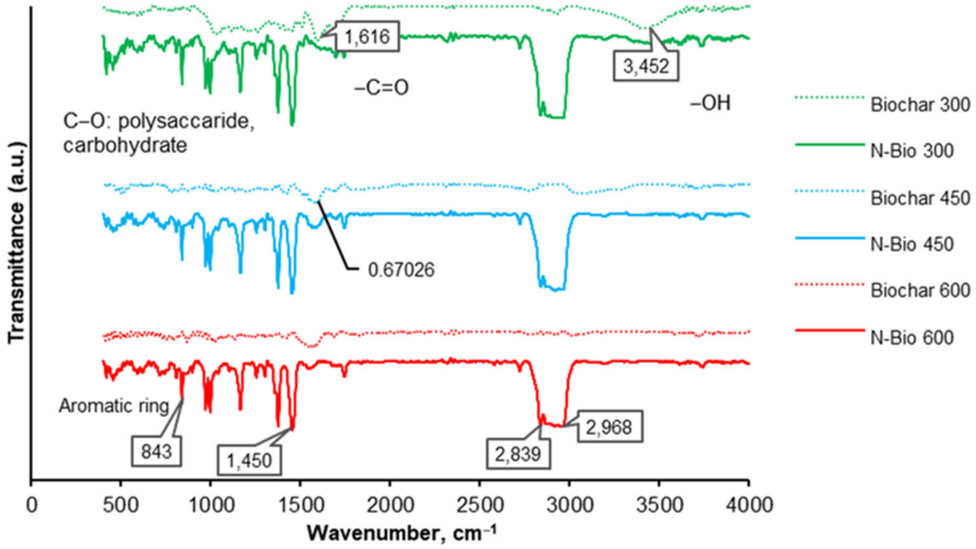

Fig 6. FTIR spectra of biochar samples pre- and post-adsorption

of the three types of biochar. The time to reach saturation adsorption ranges from 15 to 30 min. The NH_4^+ adsorption process fits to the pseudo-second-order kinetic model. The Freundlich and pseudo-second-order kinetics models, as well as combined with FTIR analysis, confirmed that the NH_4^+ adsorption process based on ion exchange and hydrogen bonding. The study showed that biochar derived from macadamia husks can be applied to treat wastewater containing high NH_4^+. In the future, the post-adsorption product can be utilized as fertilizer for agriculture.

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■ CONFLICT OF INTEREST

The author declares no conflict of interest.

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