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Effect of pyrolysis conditions on chemical properties of carbonized rice husks for efficient NH_4^+ adsorption

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Abstract

Ammonium ions (NH_4^+) are commonly found in contaminated water and are a contributing factor to water eutrophication. Carbonized rice husk, derived from various biomass sources, possesses a porous structure, and its characteristics are influenced by the feedstock and pyrolysis conditions. Hence, this study aimed to investigate the applicability of carbonized rice husk as an absorbent for NH_4^+ removal. The adsorption kinetics were analyzed using the Pseudo-first-order and Pseudo-second-order models, while the adsorption characteristics were assessed using the Langmuir and Freundlich isotherms. The adsorption rate of NH_4^+ by carbonized rice husk increased until 240 min and then gradually approached equilibrium state. Notably, the highest NH_4^+ adsorption rate was observed in pH 7.1 carbonized rice husk 36.045 mg/g·min. Moreover, the NH_4^+ adsorption capacity exhibited an increase with increasing concentration and quantity of the solution. The pH of the carbonized rice husk was found to influence the NH_4^+ adsorption process, with higher pH values corresponding to increased NH_4^+ adsorption rates. The NH_4^+ sorption rate carbonized rice husk was higher in pH 11.0 at 31.440 mg/g compared to pH 6.1 (7.642 mg/g) and pH 7.1 (10.761 mg/g). These findings highlight the impact of pyrolysis conditions on the adsorption characteristics of carbonized rice husk.

Keywords Adsorption, Ammonium ion (NH_4^+), Biochar, Pyrolysis condition

Introduction

Agricultural activities, encompassing the application of inorganic and organic fertilizers, irrigation, and tillage, play a significant role in the escalation of nitrogen losses and the deterioration of soil quality within soil ecosystems [1]. Of particular concern is the prevalence of ammonium ions (NH_4^+), the most common form of nitrogen, which can induce various physiological disorders in plants and contribute to environmental pollution, such as water eutrophication in rivers, lakes, and reservoirs [2]. Previous studies have explored diverse experimental approaches aimed at removing NH_4^+ from aquatic ecosystems, employing physical, chemical, and biological technologies [1]. However, specific chemical methods face limitations due to the extensive use of chemical materials and the potential for secondary pollutions, while biological methods encounter challenges associated with strict application conditions [3]. Consequently, physical methods are often favored owing to their simplicity in management, faster effects, and ease of practical implementation. Among physical methods, sorption-based removal has emerged as an efficient and relatively cost-effective approach [4]. The physical and chemical adsorption by various adsorbents, including zeolite, bentonite, biochar, activated carbon, silica gel,

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and aluminum oxides, have been investigated in prior research for NH_4^+ removal [5–7]. However, the adsorption capacity of NH_4^+ varies among different adsorbents, and the efficacy of specific adsorbents relies on their distinct properties [1]. Consequently, there exists a need for a study that evaluates the adsorption capacity based on the characteristics of adsorbents, leading to the development of highly efficient adsorbents.

The adsorption mechanism of carbonized rice husk involves a combination of physical adsorption, chemical adsorption, and electrostatic interaction, which collectively contribute to the effective removal of contaminants from aqueous solution [7, 8]. The physical adsorption by carbonized rice husk occurs when contaminants are attracted to the surface of carbonized rice husk through weak intermolecular forces [8]. Chemical adsorption, also known as chemisorption, involves the formation of chemical bonds between contaminations and the functional groups present on the surface of carbonized rice husk. In general, these functional groups involve the hydroxyl (-OH), carboxyl (-COOH), and amine (-NH₂) groups [8, 9]. Finally, electrostatic interactions occur when charged contaminants interact with charged sites on the surface of carbonized rice husk [8].

Agricultural carbide, such as biochar, refers to a solid carbon-rich product obtained through the thermochemical conversion of diverse agricultural biomass and organic wastes under oxygen-limited conditions [7–12]. Carbonized agricultural residue contributes to carbon sequestration, aids in soil pH regulation, enhances soil moisture levels, and adsorbs nutrient content through its porous structure and various functional groups on its surface [13]. The physical and chemical properties of carbonized agricultural residues are influenced by factors such as the type of biomass used, pyrolysis conditions, and pyrolysis technologies employed [14]. These unique characteristics make carbide a promising adsorbent for efficiently absorbing NH_4^+ from aqueous solutions and improving soil moisture levels. Agricultural carbide offers distinct advantages over commonly used adsorbents such as bentonite, zeolite, activated carbon, and silica gel owing to its diverse feedstock sources, low cost, and optimized conditions [5–7]. While several researchers have investigated the use of biochar as an adsorbent for NH_4^+ removal from aqueous solutions [2, 5, 7, 15], studies specifically focusing on the adsorption efficiency based on the characteristics of carbonized agricultural residues are still lacking [16]. Therefore, additional research and understanding are necessary regarding the adsorption capacity based on characteristics such as the pH of the carbonized agricultural residue.

The objectives of this study were as follows: (1) to evaluate the chemical characteristics of carbonized rice husk produced under different pyrolysis conditions, including pH, surface area, carbon content, and its functional groups (2) to investigate the adsorption capacity of NH_4^+ by carbonized rice husk manufactured from different pyrolysis conditions and investigate the factors influencing the adsorption process, such as contact time, initial concentration of NH_4^+, and quantity of carbonized rice husk, and (3) to identify the statistical correlations between the specific characteristics of carbonized rice husk and its adsorption capacity for NH_4^+. Additionally, the study aimed to provide insights into the potential application of carbonized rice husk as an efficient and cost-effective adsorbent for NH_4^+ removal in water treatment or soil remediation processes.

Materials and methods
Preparation of biochar and ammonium ion solution
Carbonized rice husks were sourced from Purnnature (Suncheon, South Korea) and Yoogi Industry (Gochang, South Korea), having been produced under different pyrolysis conditions. To prepare the carbide samples, the carbonized rice husks were thoroughly washed with deionized water to remove impurities and subsequently oven-dried at 80 °C for 48 h. The dried samples were then categorized based on the pH of the carbonized rice husks, specifically pH 6.1, pH 7.1, and pH 11.0 carbide. For the pH 6.1 carbonized rice husk, it was obtained by subjecting it to pyrolysis at a temperature of 330 °C for a period of 15 min and the pH 7.1 carbonized rice husk was produced at a relatively higher pyrolysis temperature (400 °C) and time (20 min). The production of pH 11.0 carbonized rice husk involved subjecting it to pyrolysis at a temperature of 600 °C for a duration of 30 min

Table 1 Pyrolysis conditions and chemical properties of the carbonized rice husks

Parameters		Carbonized rice husk		
Temp.	(°C)	330	400	600
Time	(min)	15	15	30
pH	(1:10, H₂O)	6.10 ± 0.01	7.10 ± 0.02	11.00 ± 0.01
EC	(dS/m)	11.49 ± 1.62	9.50 ± 0.83	6.59 ± 0.13
SA	(m²/g)	2.55 ± 0.01	6.49 ± 0.02	5.30 ± 0.00
T-C	(%)	42.33 ± 0.84	43.47 ± 0.12	55.50 ± 0.30
T-N		0.40 ± 0.02	0.40 ± 0.05	0.60 ± 0.01
T-H		5.39 ± 0.11	5.32 ± 0.03	2.11 ± 0.03
T-O		34.61 ± 0.59	32.50 ± 1.33	5.88 ± 1.98
H:C ratio		1.52 ± 0.00	1.46 ± 0.00	0.45 ± 0.01
O:C ratio		0.61 ± 0.01	0.56 ± 0.00	0.08 ± 0.02
(O + N):C ratio		0.33 ± 0.00	0.30 ± 0.01	0.05 ± 0.01

Temp. Temperature, *H₂O* Distilled water, *EC* Electrical conductivity, *SA* BET surface area, *T-C* Total carbon contents, *T-N* Total nitrogen contents, *T-H* Total hydrogen contents, *T-O* Total oxygen contents

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(Table 1). These pyrolysis conditions were individually tailored to differentiate the carbonized rice husks based on their pH and established based on the findings by [14].

To prepare the NH_4^+ solution, ammonium chloride (NH_4Cl, Extra pure, Samchun Chemical, Seoul, Korea) was dissolved in deionized water. Different concentrations of NH_4^+ solutions (15, 80, 120, 200, 300 and 700 mg/L) were obtained by diluting the initial 1000 mg/L NH_4^+ solution with deionized water. The pH of the NH_4^+ solution was adjusted to a range of pH 5.5–6.0 using 0.1 M hydrochloric acid (HCl) and sodium hydroxide (NaOH).

Chemical properties of carbonized rice husk
The pH and electrical conductivity (EC) of the carbonized rice husks were determined using a Benchtop Meter equipped with pH and EC probes (ORION™ Versa Star Pro™, Thermo Scientific Inc., Waltham, Massachusetts, USA) at a ratio of 1:10 (w/v). The surface area of the rice husk carbides was measured using a gas-adsorption method with a Surface area analyzer (ASAP 2420, 88 Micromeritics Inc., Norcross, Georgia, USA), analyzing the sorption curves of nitrogen gas. The total carbon (T-C), total nitrogen (T-N), total hydrogen (T-H), and total oxygen (T-O) content of the carbonized rice husks were measured using an Elemental analyzer (TruSpec Micro, Leco, Michigan, USA). Based on the elemental analysis results, the hydrogen-to-carbon ratio (H:C ratio), oxygen-to-carbon ratio (O:C ratio), and hydrogen-to-sum of oxygen and nitrogen ((O+N):C ratio) were calculated. The functional groups on carbonized rice husk's surface were analyzed using a Fourier transform infrared spectroscopy (FT-IR, Spectrum Two, Perkin Elmer, Waltham, Massachusetts, USA).

Adsorption kinetics experiments
For the adsorption kinetic test, 0.25 g of carbonized rice husks were added to a 50 mL centrifuge tube containing 40 mL of a 200 mg/L NH_4^+ solution at 20 °C. The mixture was then vibrated at 210 rpm. Subsamples were collected at specific time intervals of 30, 60, 120, 360, and 720 min. The residual NH_4^+ concentrations in the subsamples were measured using a UV/Vis-spectrophotometer based on the Indophenol blue method [17]. The amount of NH_4^+ adsorbed by the carbonized rice husks was calculated using Eq. 1.

$$q_t = (C_o - C_e) \times V/W \tag{1}$$

Where, q_t represents the amount of NH_4^+ adsorbed by the carbonized rice husks at a given time (mg/g), C_o is the initial concentration of NH_4^+ solution (mg/L), C_e is the NH_4^+ concentration in the solution at a specific time

(mg/L), V is the volume of the solution containing NH_4^+ (L), and W is the mass of the carbonized rice husks (g). The obtained results were fitted to two typical kinetic models: the Pseudo-first-order model (Eqs. 2 and 3) and the Pseudo-second-order model (Eq. 4–8). The linear forms of these kinetic models can be found in Additional file 1: Table S1.

Adsorption isotherm experiments
Adsorption isotherms are commonly employed to describe the interaction between adsorbates and adsorbents at equilibrium [15, 18]. In this study, the Langmuir and Freundlich isotherms were utilized to analyze the experimental results. The linear forms of the Langmuir isotherms (Eq. 9 to 13) and the Freundlich isotherm (Eq. 14) can be found in Additional file 1: Table S2. The Langmuir isotherm is suitable for describing monolayer adsorption of the adsorbate on the adsorbent, while the Freundlich isotherm is commonly used to represent chemical adsorption on heterogeneous surfaces [2, 19].

To investigate the effect of carbonized rice husk quantity on NH_4^+ adsorption, NH_4^+ solutions (120 mg/L) in 40 mL volumes were treated with different application rates of carbonized rice husk (1, 5, 10, 30, and 50 g/L) in 50 mL centrifuge tubes. The mixed samples were agitated using an electrical shaker at room temperature (20 ± 1 °C) and 210 rpm. After shaking for 4 h, the NH_4^+ solutions were filtered to separate the solid and liquid components, and supernatant was analyzed using a UV/Vis-spectrophotometer based on the Indophenol blue method [17]. The duration of the adsorption reaction was determined based on a prior kinetic test conducted (Additional file 1: Figure S1).

To investigate the effect of the initial NH_4^+ concentration using the isotherm models, 0.25 g of carbonized rice husks was treated in NH_4^+ solutions of varying concentrations (15, 80, 300, and 700 mg/L). The mixed samples were shaken using the electrical shaker for 4 h at room temperature (20 ± 1 °C) and 210 rpm. Once the NH_4^+ solution reached equilibrium, the concentration of the filtrate was measured using a UV/Vis-spectrophotometer with the Indophenol blue method [17]. Additionally, the same method and conditions were applied to assess the effect of carbonized rice husk quantity on NH_4^+ adsorption.

Statistical analysis
All experiments were performed in triplicate. Statistical correlations between the NH_4^+ adsorption characteristics were analyzed using IBM SPSS Statistics 26 (IBM, New York, USA). Furthermore, the data were subjected to analysis of variance (ANOVA), and the average values

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were utilized for conducting Duncan's multiple range test to compare the means.

Results and discussion

Characterization of carbonized rice husks

Table 1 presents the analysis results of the chemical properties of the carbonized rice husks and the corresponding pyrolysis conditions. The variation in pyrolysis temperature and time had a significant impact on the chemical characteristics of the carbonized rice husk. The pH of the carbonized rice husks exhibited a sharply increase as the pyrolysis conditions were raised from 330 to 600 °C and from 15 to 30 min. This increase can be attributed to the degradation of organic acids and carbonates during pyrolysis, resulting in a higher ratio of alkali salts in the carbonized rice husks [20]. Moreover, it suggests that increasing the pyrolysis conditions promoted the development and formation of highly porous structures in the carbonized rice husk produced at high temperatures and longer durations [21]. Notably, the carbonized rice husk produced at 400 °C at 15 min exhibited a higher surface area compared to the other conditions.

Pyrolysis temperature played a crucial role in the elemental composition of the carbonized rice husk. As the pyrolysis temperature increased from 330 to 600 °C, the T-C content increased from 41.30 to 54.90%, while the T-N content increased from 0.40 to 0.60%. However, the T-H and T-O contents significantly decreased from 5.39 to 2.11% and from 34.61 to 5.88%, respectively. It is known that deoxygenation, dehydration, and carbonization are the main reactions occurring at temperatures

between 450 and 650 °C [22]. Furthermore, it is worth noting that the T-O content significantly decreased with increasing pyrolysis conditions (temperature and time), while the T-C content only showed a slight increase from 41.30 to 54.90%, suggesting that higher temperatures and longer durations contribute to the enhanced stability of the carbide.

The H:C ratio can indicate the aromaticity of the carbonized rice husk, while the O:C ratio and (O+N):C ratio can indicate its polarity [23]. In this study, the carbonized rice husk produced at 400 °C for 15 min exhibited the highest H:C ratio, while the carbonized rice husk manufactured at 600 °C for 30 min had the lowest H:C ratio. Furthermore, the H:C ratio, O:C ratio, and (O+N):C ratio tended to decrease as the pyrolysis temperature and time increased. These findings suggest that pyrolysis conditions influence the aromaticity and polarity of the carbonized rice husk, with higher pyrolysis temperature and longer duration leading to stronger hydrophobic characteristics. It is worth noting that carbonized agricultural residues with a low O:C ratio and (O+N):C ratio can potentially contribute to environmental pollution through generation of volatile matter during dehydration and depolymerization processes [24].

Figure 1 presents the FT-IR analysis results of functional groups on the surface of carbonized rice husks. The presence of the secondary amide group, indicated by the -NH bond in the range of 3300–3325 cm^{-1}, diminished as the pyrolysis temperature and time increased. Moreover, carbonyl group, represented by the C=C bond in the range of 1640–1660 cm^{-1}, showed a similar
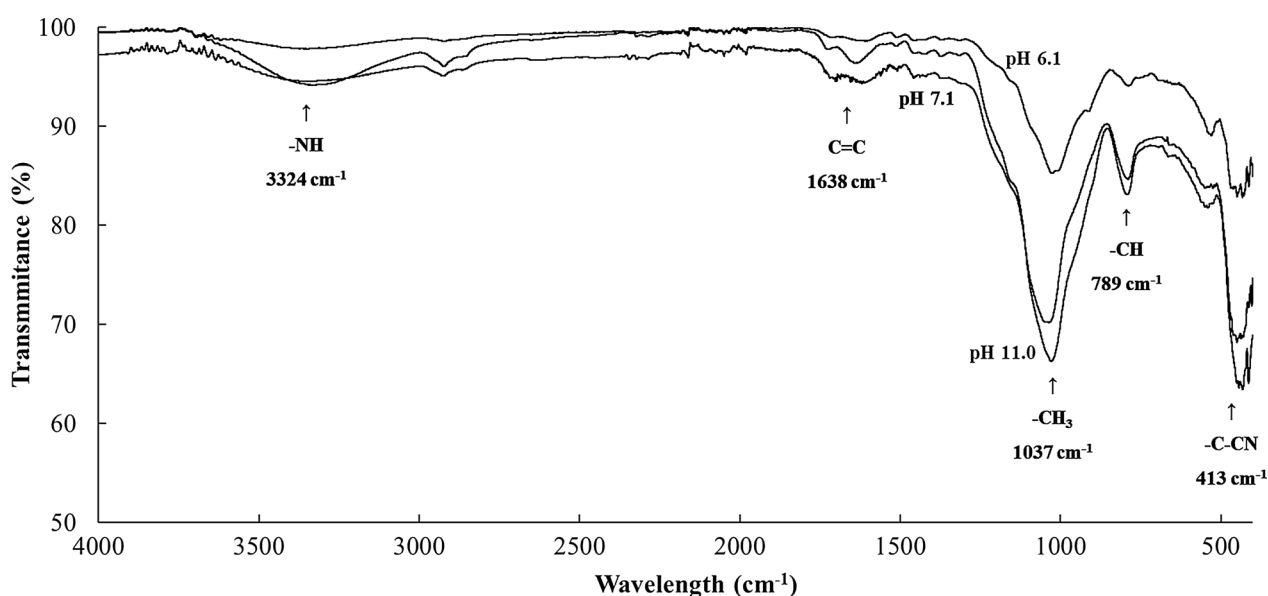

Fig. 1 FT-IR spectrum of pH 6.1, pH 7.1 and pH 11.0 carbonized rice husk

trend to the secondary amide group. As the pH of carbonized rice husk increases from pH 6.1 to pH 7.1 and pH 11.0, the intensities of both the -CH_3 bond (1000–1050 cm^{-1}) and the -C-CN bond (400–420 cm^{-1}) show a significant decrease. At higher pyrolysis conditions, the FT-IR spectra exhibit more dynamic changes, indicating the potential rupture of various functional groups and the progressive carbonization process.

Adsorption kinetics

The adsorption rates of NH_4^+ by carbonized rice husks initially increased rapidly within the first 240 min and then gradually slowed down until reaching equilibrium (Additional file 1: Figure S1A). The concentration of NH_4^+ in the NH_4^+ solution also exhibited a rapid decrease up to 240 min (Additional file 1: Figure S1B), followed by a gradual reduction towards equilibrium. These kinetic results were evaluated using the PFO and the PSO model. However, it was observed that the results did not satisfactorily fit the type 1 and type 2 of
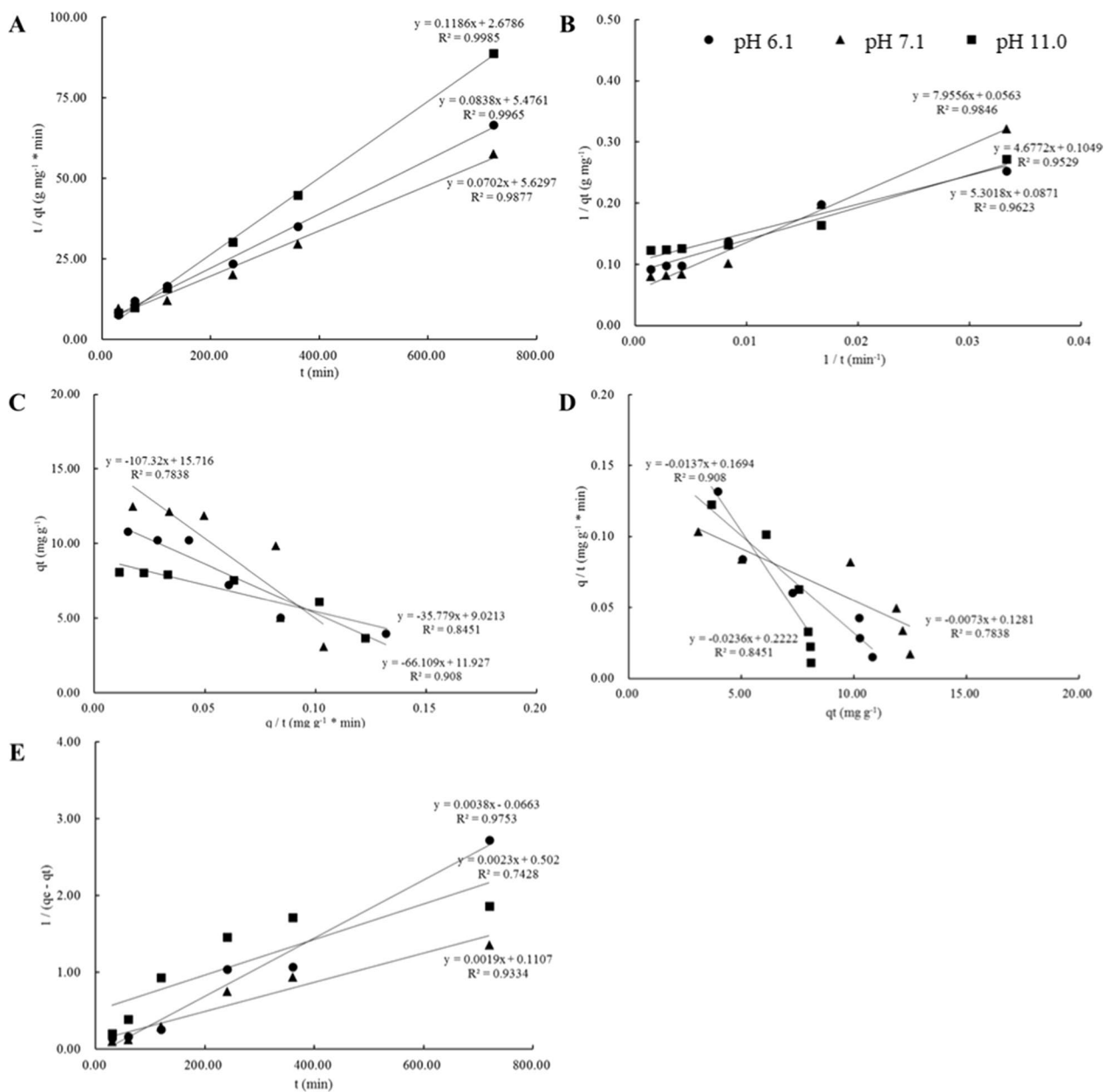

Fig. 2 Kinetic curves fitted by **A** type 1, **B** type 2, **C** type 3, **D** type 4 and **E** type 5 of Pseudo-second-order model

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Table 2 Kinetic parameters of NH_4^+ sorption on the carbides for Pseudo-second-order model

Carbonized rice husk	Type	K_2 (g/mg · min)	h	q_e (mg/g)	R^2
pH 6.1	Type 1	26.004	0.183	11.933	0.997
pH 7.1		36.045	0.178	14.245	0.988
pH 11.0		26.541	0.373	8.432	0.999
pH 6.1	Type 2	24.862	0.189	11.481	0.962
pH 7.1		39.656	0.126	17.762	0.985
pH 11.0		19.430	0.214	9.533	0.953
pH 6.1	Type 3	0.001	0.015	11.927	0.908
pH 7.1		0.001	0.009	15.716	0.784
pH 11.0		0.003	0.028	9.021	0.845
pH 6.1	Type 4	0.001	0.169	12.365	0.908
pH 7.1		0.000	0.128	17.548	0.784
pH 11.0		0.003	0.222	9.415	0.845
pH 6.1	Type 5	0.004	0.864	15.083	0.975
pH 7.1		0.002	0.155	9.033	0.993
pH 11.0		0.002	0.009	1.992	0.743

K_2 constant of pseudo-second-order model, *h* initial adsorption rate of carbide, q_e, total amount of NH_4^+ adsorbed by the biochar, R^2, coefficient of determination

the PFO model, as the substituted consequences showed duality (Additional file 1: Figure S2). Therefore, it was determined that the data were more appropriate for the application of the PSO model (Fig. 2). The kinetic parameters calculated using the PFO model are listed in Additional file 1: Table S3, and the corresponding curves of substituted kinetic data are shown in Additional file 1: Figure S2. The kinetic results were divided into sections based on the 240-minute mark (Additional file 1: Table S3). The reaction constant (K_1) exhibited a sharp decrease after 240 min, indicating that equilibrium had been reached. Additionally, the adsorption quantity (q_e) also decreased drastically after 240 min.

The kinetic results were then substituted into the PSO model to calculate the q_e and the reaction constant (K_2) over the entire duration. Among the different types of PSO, type 1 yielded a higher coefficient of determination ($R^2 > 0.980$) compared to the other types, and the calculated q_e values were 11.933 mg/g, 14.245 mg/g, and 8.432 mg/g for carbonized rice husks with pH 6.1, 7.1, and 11.0, respectively (Table 2). The PSO model was also able to calculate the h, which represents the initial sorption rate of the carbonized rice husk, based on the K_2 and the q_e. Unlike the q_e, the values of h were 0.18, 0.18, and 0.37, and they tended to increase with higher pH value of the carbonized rice husks. The kinetic parameters computed by the PSO model are presented in Table 2, and the corresponding kinetic curves are shown Fig. 2. These results indicate that the NH_4^+ adsorption

kinetics onto the different pH levels of the carbonized rice husk can be satisfactorily represented by the PSO model, suggesting that the sorption process is chemically controlled [25].

Adsorption isotherms

The NH_4^+ adsorption capacity onto carbonized rice husks was found to increase with an increase in the NH_4^+ concentration of the solution. Notably, the adsorption ability was observed to increase more rapidly at lower NH_4^+ concentrations compared to relatively higher concentrations (Additional file 1: Figure S3). The experimental results were fitted using the linear form of the Langmuir and Freundlich isotherms (Additional file 1: Table S2). The experimental parameters and corresponding curves are presented in Table 3; Fig. 3, respectively. The high R^2 values indicate that models with higher R^2 values can accurately describe the NH_4^+ sorption process compared to other models. In this study, type 1 and type 5 of the linear form of the Langmuir isotherm exhibited the highest R^2 value ($R^2 > 0.980$) compared to other types of the Langmuir isotherm and Freundlich isotherm (Fig. 3). These results indicate that the NH_4^+ adsorption onto carbonized rice husk follows a single-molecule coverage process. The NH_4^+ sorption rate by carbonized rice husk was higher in type 5 of the Langmuir isotherm compared to type 1 of the Langmuir isotherm, with values of 7.642 mg/g, 10.761 mg/g, and 31.440 mg/g according to the pH of the carbonized rice husk (Table 3). Additionally, there was a rapid increase in the quantity of NH_4^+ adsorbed by the pH 11.0 carbonized rice husk, while there was only a slight difference observed between pH 6.1 and pH 7.1 carbonized rice husk. However, the parameter b, which represents the binding capacity of the carbonized rice husk, showed no difference among the types of the Langmuir isotherm. These results indicate that the pH of the carbonized rice husk can affect the adsorption ability in the sorption process.

The NH_4^+ adsorption experiments at different carbonized rice husk dosages were evaluated using the linear form of the Langmuir and Freundlich isotherm (Additional file 1: Table S2). The substituted results are presented in Table 4; Fig. 4, respectively. The NH_4^+ sorption capacity of the rice husk carbide increased with an increase in the dosage of the carbonized rice husk, and the sorption dose gradually increased as the quantity of the adsorbent increased (Additional file 1: Figure S4). Additionally, there was no statistically significant difference observed in the NH_4^+ adsorption rate based on the pH of the carbonized rice husk. In the adsorption test using different application rates of the carbonized rice husk, type 3 and type 4 of the Langmuir isotherm exhibited high R^2 value ($R^2 > 0.990$), consistent with
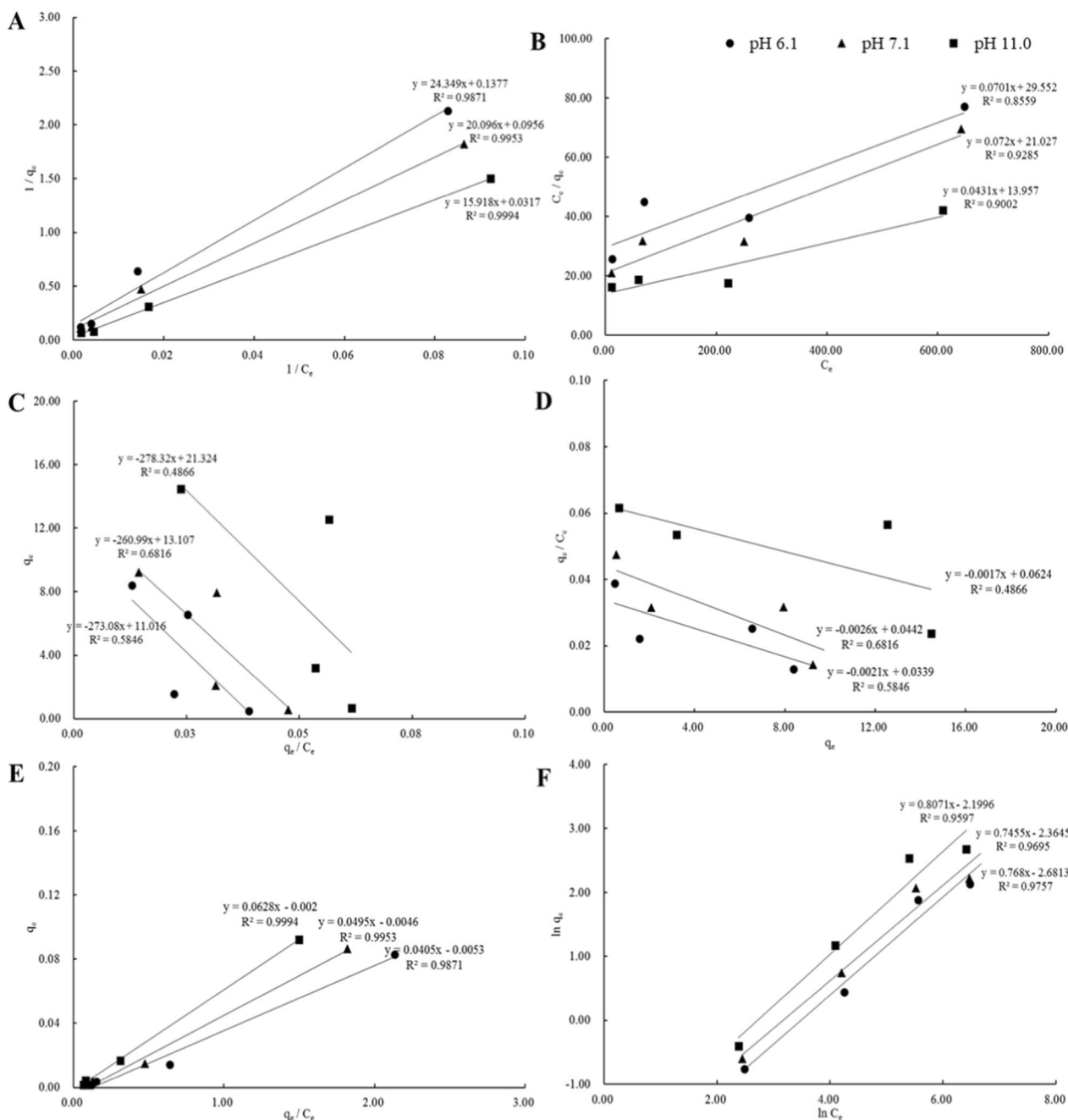
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Fig. 3 Effect of initial NH_4^+ concentration on adsorption by the carbonized rice husks and **A** type 1, **B** type 2, **C** type 3, **D** type 4, **E** type 5 of Langmuir isotherm and **F** Freundlich isotherm fit related to the sorption of NH_4^+ onto the carbonized rice husks

the Langmuir isotherm (Fig. 4). The adsorption results obtained using type 4 of the Langmuir isotherm were 0.425 mg/g, 0.538 mg/g, and 1.117 mg/g for carbonized rice husk with the pH values of 6.1, 7.1, and 11.0, respectively, which were higher than the values obtained using type 3 of the Langmuir isotherm. The binding capacity (b) of each rice husk carbide was 0.008 for both type

3 and type 4 of the Langmuir isotherm (Table 4). The change in sorption dose according to the pH of carbonized rice husk exhibited a similar trend to the experiments performed by varying the NH_4^+ concentration in an aqueous solution.

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Table 3 Langmuir and Freundlich isotherm parameters for the sorption of NH_4^+ onto the carbonized rice husks depend on the concentration of solution

Isotherm	Type	Parameters	pH 6.1	pH 7.1	pH 11.0
Langmuir	Type 1	q_m (mg/g)	7.262	10.460	31.546
		b (L/mg)	0.006	0.005	0.002
		R^2	0.987	0.995	0.999
	Type 2	q_m (mg/g)	14.265	13.889	23.202
		b (L/mg)	0.002	0.003	0.003
		R^2	0.856	0.929	0.900
	Type 3	q_m (mg/g)	11.016	13.107	21.324
		b (L/mg)	0.004	0.004	0.004
		R^2	0.585	0.682	0.487
	Type 4	q_m (mg/g)	16.143	17.000	36.706
		b (L/mg)	0.002	0.003	0.002
		R^2	0.585	0.682	0.487
	Type 5	q_m (mg/g)	7.642	10.761	31.400
		b (L/mg)	0.005	0.005	0.002
		R^2	0.987	0.995	0.999
Freundlich	Type 1	K_F	0.068	0.094	0.111
		n	1.302	1.341	1.239
		R^2	0.976	0.970	0.960

q_m dosage of NH_4^+ adsorbed by the single layer of carbide, *b* binding capacity, R^2 coefficient of determination, K_F indicator of the carbide's adsorption capacity, *n* adsorption strength of carbide

Table 4 Langmuir and Freundlich isotherm parameters for the sorption of NH_4^+ onto the carbonized rice husks depend on the dose of absorbent

Isotherm	Type	Parameters	pH 6.1	pH 7.1	pH 11.0
Langmuir	Type 1	q_m (mg/g)	0.475	0.594	1.986
		b (L/mg)	0.008	0.008	0.007
		R^2	0.972	0.964	0.933
	Type 2	q_m (mg/g)	0.475	0.596	1.846
		b (L/mg)	0.008	0.008	0.007
		R^2	0.962	0.956	0.803
	Type 3	q_m (mg/g)	0.421	0.538	1.095
		b (L/mg)	0.008	0.008	0.008
		R^2	0.999	0.999	0.996
	Type 4	q_m (mg/g)	0.425	0.538	1.117
		b (L/mg)	0.008	0.008	0.008
		R^2	0.999	0.999	0.996
	Type 5	q_m (mg/g)	0.570	0.463	1.779
		b (L/mg)	0.008	0.008	0.007
		R^2	0.964	0.972	0.933
Freundlich	Type 1	q_m (mg/g)	13.889	13.388	11.177
		K^F	0.000	0.000	0.000
		n	0.125	0.149	0.250
		R^2	0.803	0.815	0.688

q_m dosage of NH_4^+ adsorbed by the single layer of carbide, b binding capacity, R^2 coefficient of determination, K_F indicator of the carbide's adsorption capacity, *n* adsorption strength of carbide

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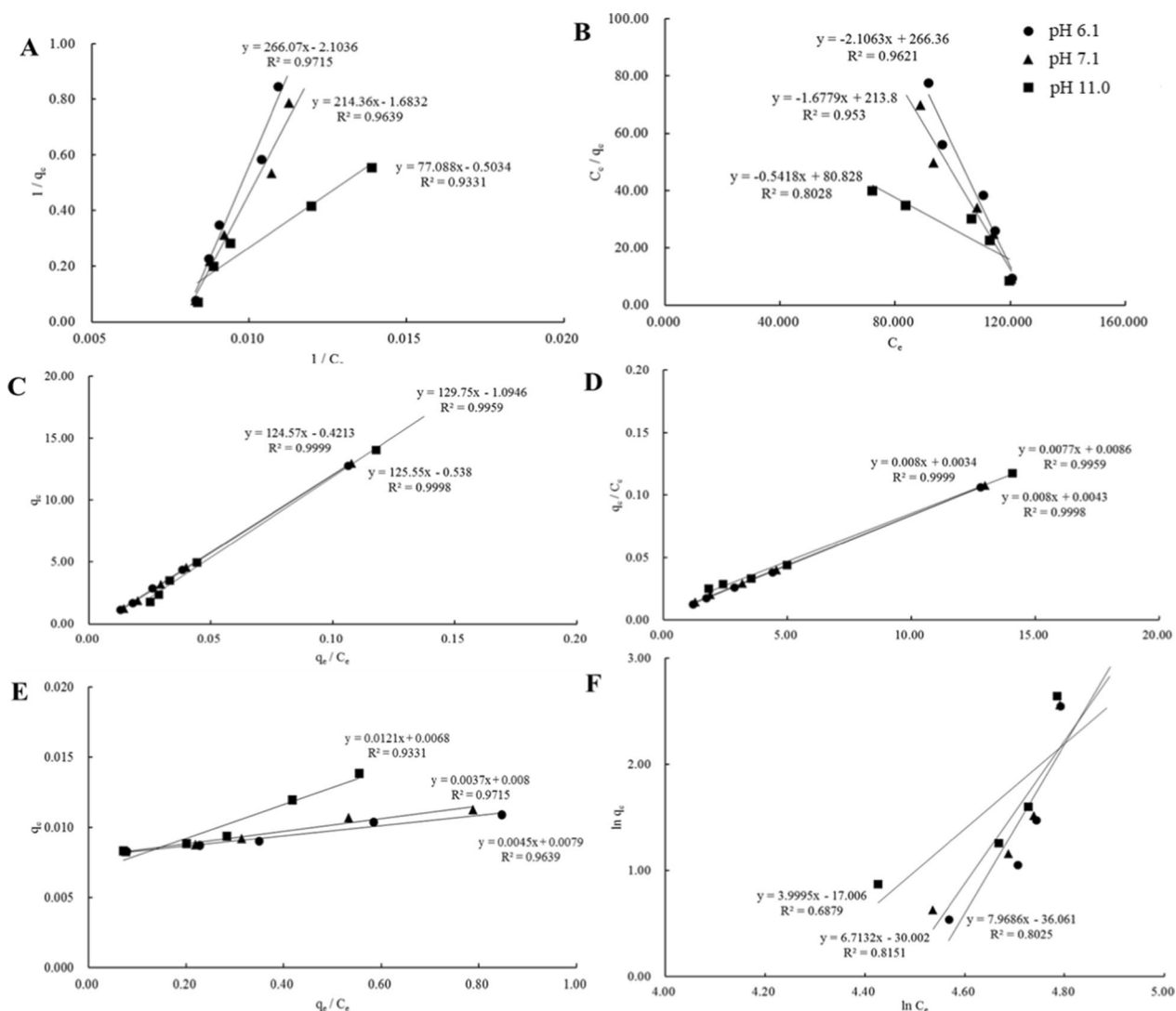
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Fig. 4 Effect of adsorbent dosage in solution on adsorption by the carbonized rice husks and **A** type 1, **B** type 2, **C** type 3, **D** type 4, **E** type 5 of Langmuir isotherm and **F** Freundlich isotherm fit related to the sorption of NH_4^+ onto the carbonized rice husks

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13765-023-00806-1.

Additional file 1: Table S1. The linear forms of the kinetic models used in this experiments. **Table S2.** The linear form of Langmuir and Freundlich isotherm. **Table S3.** Kinetic parameters of NH_4^+ sorption on the carbonized rice husk for Pseudo-first-order model. **Figure S1.** Correlation between (A) carbonized rice husk's pH, contact time and NH_4^+ adsorption quantity, (B) carbonized rice husk's pH, contact time and NH_4^+ concentration of solution. **Figure S2.** Kinetic curves fitted by (A) type 1 and (B) type 2 of Pseudo-first-order model. **Figure S3.** Correlation between adsorption capacity and NH_4^+ concentration of solution. **Figure S4.** Correlation between adsorption capacity and amount of carbonized rice husks in NH_4^+ solution.

Author contributions

Conceptualization, Y-GK, T-KO and J-KS; data curation, Y-GK, J-HL and J-YL; formal analysis, Y-GK, J-HK and J-YL; investigation, Y-GK, T-KO and J-KS; methodology, T-KO and J-KS; supervision, T-KO and J-KS; validation Y-GK and J-HL; roles/writing—original draft, Y-GK and J-HL; writing—review & editing, T-KO and J-KS.

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