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Tofu wastewater treatment innovation: Effectiveness of natural zeolite as an adsorbent in the ammonium adsorption process

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ABSTRACT

Waste from tofu production contains high ammonia levels in the form of ammonium, which can pollute the environment when discharged without prior treatment. Using natural zeolite as an adsorbent in treating ammonium contained in tofu waste is expected to effectively reduce the ammonium content, as natural zeolite has a high adsorption capacity. This research aims to analyze the ability of natural zeolite from Bayah, Indonesia, as an adsorbent in reducing ammonium content in tofu waste by integrating factors that influence the adsorption process such as adsorbent dose, stirring speed, adsorbent particle size, and contact time, to obtain optimal adsorption operating conditions. To achieve the research objectives, observations were conducted over a wide range: adsorbent sizes of 40–100 mesh, adsorbent mass of 1–5 grams/100 ml waste, stirring speeds of 400 and 600 rpm, and contact time of 60 minutes. The research results show that reducing the adsorbent size (40–100 mesh) and increasing the adsorbent dose (1–5 grams) has a positive impact on improving the percentage of ammonium removal achieved, but increasing the stirring speed (from 400 to 700 rpm) has the opposite effect, resulting in a decrease in the percentage of ammonium removal produced. Optimum conditions obtained at a mass of 5 grams, zeolite size of 100 mesh, and stirring speed of 400 rpm for 60 minutes, resulting in an ammonium removal percentage of 70.13%. The results of this research show that the use of natural zeolite has good prospects as an adsorbent in tofu waste treatment, although it still needs to be improved so that the percentage of ammonium removal approaches 100%.

Keywords: liquid waste, adsorption kinetics, X-ray diffraction analysis, mass transfer rate.

INTRODUCTION

Tofu is a processed food containing protein and is widely consumed by the Indonesian people, so this industry is extensive and dynamic (Ningsih et al., 2024). The tofu production process generates liquid waste containing ammonia dissolved in water in the form of NH_4OH, often called ammonia-water (Equation 1) (Chung et al., 2024), from decomposed protein (Edwards et al., 2023), which is the leading cause of unpleasant odors in tofu waste (Gao et al., 2024). Ammonium, as one of the pollutants in tofu wastewater, has a concentration of 11–16 mg/L (Elystia et al., 2023) or even higher. Meanwhile, the maximum permitted ammonium content to be discharged into the river

must meet established quality standards; for example, in Indonesia, the highest permitted ammonium content is 0.5 mg/L (Fitriana et al., 2023).

$$NH_3 + H_2O \rightleftharpoons NH_4OH \quad (1)$$

To avoid adverse environmental impacts, treating tofu wastewater containing ammonium is necessary. The degradation of ammonium in wastewater can be accomplished through various methods, including biological treatment and photocatalysis techniques (Liu et al., 2023), ozonation (Ma et al., 2023), electrochemical oxidation (Meng et al., 2023), and adsorption (Detho et al., 2024). In this study, the adsorption method using Bayah natural zeolite (BNZ) was chosen because it utilizes abundant-underutilized natural resources and has a pore diameter of 32.57 Å (Nuryoto et al., 2016), which is larger than the diameter of ammonia molecules at 2.6 Å (Padinjarekutt et al., 2023). Therefore, BNZ has the potential to be used as an adsorbent and can work effectively to adsorb ammonia dissolved in water (NH_4OH). Theoretically, the adsorption of ammonium using zeolite adsorbent with active cation groups (natrium (Z-Na^+)) can be written as shown in Equation 2 (Soetardji et al., 2015) and can be illustrated in Figure 1.

$$Z\text{-}\ Na^+ + NH^{4+} \rightarrow Na^+ + Z\text{-}NH^{4+} \quad (2)$$

Essentially, zeolites that have been used to adsorb ammonium and have become saturated can later be used as fertilizer for plants because plants highly need the nitrogen content in ammonium to form proteins, chlorophyll, and nucleic acids in plants. Additionally, zeolites can help maintain soil structure, improve aeration, and enhance the soil's ability to retain water and contain contaminants (Kordala et al., 2024). Therefore, adsorbing ammonium using natural zeolites is a comprehensive problem-solving approach that does not create subsequent issues. Research related to ammonium/ammonia degradation using adsorption methods with zeolite adsorbents has been conducted by previous researchers (Table 1).

Table 1 shows that influential factors such as stirring, adsorbent size, contact time, and adsorbent mass result in the highest ammonium removal of only 76.48%. Therefore, this study aims to analyze the ability of natural zeolite from Bayah, Indonesia, as an adsorbent to reduce the ammonium content in tofu wastewater by integrating factors that influence the adsorption process, such as adsorbent dosage, stirring speed, adsorbent particle size, and contact time, with the expectation of obtaining optimal adsorption operating conditions. Conceptually, the effects of stirring speed, adsorbent size, and adsorbent dosage can be illustrated in Figure 1, which is further clarified by Figure 2, and can be elaborated into correlated forms as presented in Equations 3–10 (Wang et al., 2024; Melo et al., 2024).

$$\frac{dC}{dt} = -D_m \frac{dC}{\delta} \quad (3)$$

Equation 3 can be modified to:

$$\frac{dC}{dt} = k\,(C_b - C_s) \quad (4)$$

The mass transfer constant (k) is influenced by particle diameter, molecular diffusivity (Dm), and Reynolds number as written in Equation 5–7.

$$S_h = \frac{k\,d_p}{D_m} \quad (5)$$

$$S_h = 2 + 0.553\,R_e^{0.5}\,S_c^{0.33} \quad (6)$$

For the Reynolds number in a stirred system, it is expressed by Equation 7 (Maluta et al., 2024)

$$R_e = \frac{\rho\,N\,d_p^2}{\mu} \quad (7)$$

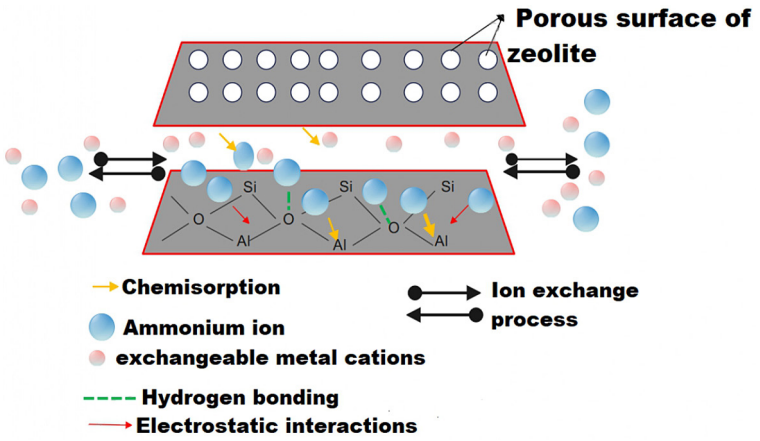

Figure 1. Illustration of ammonia adsorption using natural zeolite (based on Yadav et al., 2023)

Table 1. Research on ammonia adsorption using zeolite adsorbents

Adsorbents	Operating conditions	Performance	Reference
Synthetic zeolite and natural zeolite – China	Conducted in batch mode with an ammonium concentration of 10–200 mg/L, adsorbent concentration of 28 g/L, and stirring at 150 rpm	Maximum adsorption was achieved with synthetic zeolite at 27.46 mg/g, produced at an adsorbent concentration of 4 g/L, while natural zeolite only reached 7.61 mg/g	Zhou et al., 2024
Clinoptilolite type zeolite	Conducted in a packed bed, with zeolite size of 0–5.0 mm and flow rate of 1.62,3 L/h	The best operating conditions are a flow rate of 2.3 L/h and a zeolite size of 0.5–1 mm, which results in a 49% removal.	Muscarella et al., 2024
Natural zeolite from North Sumatra	Conducted in batch mode, with an adsorbent mass of 50 mg and ammonia concentration of 100 mg/L, stirring at 300 rpm for 3 hours, zeolite activation with 2 M HCl both with and without calcination at zeolite size of 100 mesh and stirring at 300 rpm	The best operating conditions were obtained with zeolite without calcination (Z1), which removed 40% of ammonia.	Husin et al., 2024
Clinoptilolite type zeolite	Natural zeolite was activated using 1 M NaCl for 24 hours, ammonium concentration 5–20.000 mg/L, stirring at 80 rpm, temperature 25 °C for 24 h.	The highest ammonia removal is around 35% at an ammonium concentration of 20.000 mg/L	Muscarella et al., 2023
Clinoptilolite type zeolite	This was conducted using a batch system, with zeolite particle sizes of 1–72 µm, ammonia concentration variations of 1–20 mg/L, and an adsorbent solution of 1–8 grams/100 ml solution for 2 hours.	Maximum ammonia removal of about 76.48% was achieved with an adsorbent dose of 6 g/L, contact time of 120 min, and ammonia concentration of 15 mg/L	Yadav et al., 2023

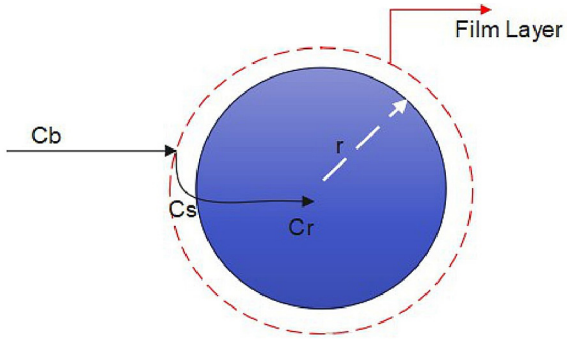

Figure 2. General illustration of the mass transfer stages of molecules from the bulk liquid to the active sites of the adsorbent

For internal diffusion, it can be written as in Equation 8

$$\frac{dC}{dt} = -D_e \frac{dCr}{dr} \tag{8}$$

Equation 8 can be modified to:

$$\frac{dC}{dt} = k_f\, m\, (C_s - C_r) \tag{9}$$

where: $D_e = D_m \frac{\varepsilon}{\sigma}$ – internal diffusion coefficient (m^2/s), *Dm* – molecular diffusion coefficient (m^2/s), $\frac{dC}{dt}$ – mass transfer rate of a compound (ammonium) (mol/m^3s), δ – film layer (m), *k* – external mass transfer constant (m/s), C_b – ammonium concentration in the bulk liquid (mol/m^3), *Cs* – ammonium concentration on the outer layer of zeolite (mol/m^3), *Sh* – Sherwood number (dimensionless), *dp* – adsorbent particle diameter (m), *N* – stirring speed (rps), *m* – adsorbent mass (gram), *kf* – internal mass transfer constant (m/s), μ – viscosity ($kg/(m \cdot s)$), *Cr* – ammonium concentration in the internal zeolite (mol/m^3), *Re* – Reynolds number (dimensionless), *Sc* – Schmidt number (dimensionless), ε – void fraction (dimensionless), σ – Tortuosity (dimensionless).

When the adsorption process has reached steady-state conditions, the external diffusion rate Equation 4 will be equal to the internal diffusion rate (Equation 9), thus becoming Equation 10.

$$k\,(C_b - C_s) = k_f\, m\, (C_s - C_r) \tag{10}$$

Therefore, based on Equations 3–10, when the stirring speed, adsorbent size, and adsorbent mass are well integrated, it is expected that the diffusion process of ammonium to the active sites of zeolite is expected to proceed well, and the adsorption process will run more optimally.

MATERIAL AND METHOD

Raw materials and research equipment

Tofu wastewater was obtained from a home-local industry in Indonesia. Natural zeolite from

Bayah (BNZ) was also sourced locally. The tofu wastewater was analyzed for ammonium content using a Hanna ammonia/ammonium checker (Italy brand) and yielded an ammonium concentration of 22.6 mg/L. The BNZ was crushed and sieved to specific sizes (40–100 mesh). It was then heated in an oven at 110 °C for 2 hours, and X-ray diffraction (XRD) analysis (Bruker's D8 series – Bruker's, Germany) was performed to determine the type of BNZ used. The use of BNZ size in the range of 40–100 mesh refers to research by Lyu et al. (2021). This research demonstrates that within this adsorbent size range, the adsorption rate (q) of N_2 can proceed effectively. Regarding the drying temperature and time of 110 °C for 2 hours, this protocol is supported by studies from Nuryoto et al. (2016) and Cundari et al. (2023). According to these studies, these specific zeolite drying conditions allow for maximal drying of the water content within the zeolite.

Experimental procedure

This research was conducted in batch mode (Figure 2). 100 ml of tofu wastewater was placed into a beaker glass, then Bayah natural zeolite of a specific size (40–100 mesh) was added with a BNZ adsorbent dose according to the predetermined variation of 1–5 grams (referring to Cundari et al. (2023), which achieved an adsorption effectiveness above 90%). The mixture was stirred at certain speeds (400 and 600 rpm referring to Narkesabad et al. (2023), which demonstrated the ability to adsorb metals with over 97% effectiveness) in the next step. After 60 minutes (referring to Intang et al., 2024), samples were taken to determine the remaining ammonium content in the solution. A Hanna brand from Italy ammonia/ammonium checker was used to determine the remaining ammonium content in the sample solution. For the procedures or stages ammonium analysis, reference was made to the standard operational procedure (SOP) contained in the Hanna Ammonia/Ammonium Checker manual (Figure 3).

Equation 11 calculates the percentage of ammonium removed from the adsorption process that has been carried out.

$$\%\, NH_4^+ = \frac{C_o - C_t}{C_o} \times 100\% \qquad (11)$$

where: $\%NH_4^+$ – percentage of ammonium removal (%), C_o – Initial ammonium concentration (mg/L), C_t – ammonium concentration at a specific time t (mg/L).

Adsorption kinetics model

In this study, calculations of adsorption kinetics models were performed, which were carried out under the best conditions that produced the highest percentage of ammonium removal. These were done to obtain adsorption rate constants that are beneficial for further development on the pilot scale and useful for predicting the percentage of ammonium removal produced at contact times besides the range tested. However, validation with experimental data must still be carried out to ensure that the model obtained is sufficiently valid to represent the adsorption process in this study. The approach taken was to use adsorption kinetics models that have often been used for adsorption processes in general, namely the pseudo-homogeneous first and second-order mathematical models (Equations 12 and 13).

$$\frac{dq_t}{dt} = k_1\,(q_e - q_t) \qquad (12)$$

$$\frac{dq_t}{dt} = k_2\,(q_e - q_t)^2 \qquad (13)$$

The values of q_t and q_e are determined using Equations 14 and 15.

$$q_t = \frac{(C_0 - C_t) \times V}{m} \qquad (14)$$

$$q_e = \frac{(C_0 - C_e) \times V}{m} \qquad (15)$$

where: q_t – amount of substance adsorbed at time t (mg/g), q_e – amount of substance

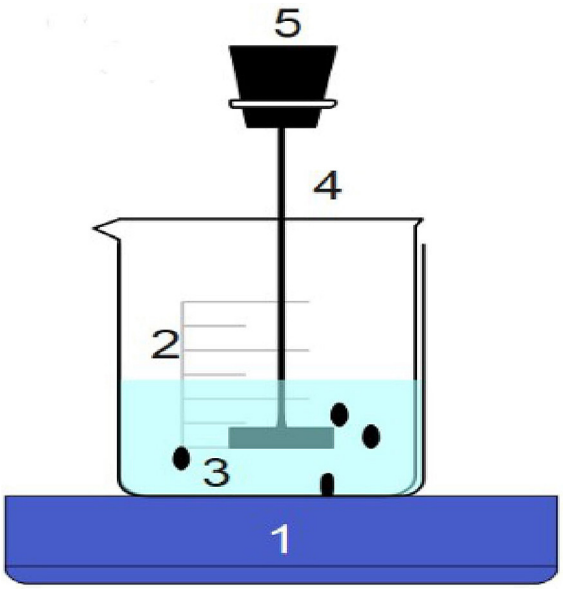

Figure 3. Illustration of ammonia adsorption process equipment: (1) hot plate, (2) 250 ml beaker glass, (3) adsorbent (BNZ) and adsorbate (tofu, wastewater), (4) stirrer, (5) stirrer motor

adsorbed at equilibrium (mg/g), k_1 – first-order adsorption rate constant (L/min), k_2 – second-order adsorption rate constant (g/mg·min), t – time (minute), C_0 – initial concentration of adsorbate in solution (mg/L), C_t – adsorbate concentration in solution at time t (mg/L), V – volume of adsorbate solution (L), m – adsorbent mass (g), dan C_e – adsorbate concentration in solution at equilibrium (mg/L).

Subsequently, the first-order and second-order mathematical models are integrated and rearranged into Equation 16 and Equation 17.

$$ln\,(q_e - q_t) = ln\,q_e - k\,t \qquad (16)$$

$$\frac{t}{q_t} = \frac{1}{k_2\,q_e{}^2} + \frac{1}{q_e}\,t \qquad (17)$$

The values of adsorption rate constants for both first-order (k_1) and second-order (k_2) were obtained by plotting $ln(q_e - q_t)$ versus t (for the first-order) and $\frac{t}{q_t}$ versus t (for the second order) and then performing a trendline analysis using Microsoft Excel.

The model's suitability was statistically evaluated using the coefficient of determination (R^2) obtained by comparing and confirming simulation data with experimental data. A good model has an R^2 value close to or equal to 1. In this condition, the experimental data and model gave overlapping curve fittings, allowing it to represent the adsorption rate phenomenon in ammonium adsorption using BNZ adsorbent.

RESULTS AND DISCUSSION

Characterization results – XRD

The XRD analysis results of BNZ (Figure 4) and comparison with the zeolite database for clinoptilolite, mordenite, and quartz types show that the BNZ structure consists of clinoptilolite with prominent peaks at 2θ: 9,8°; 13,3°; 22,4°; 29,9°; 31,92°, mordenite with prominent peaks at 2θ: 9,8°; 13,4°; 19,6°; 22,3°; 25,6°; 27,6, and quartz with peaks at 2θ: 20,9°; 26,6°. These results are similar to previous studies using BNZ, which found that BNZ consists of clinoptilolite, mordenite, and quartz types (Kurniawan et al., 2020; Irawan et al., 2021).

Effect of adsorbent dosage on ammonium removal

The effect of adsorbent dosage on ammonium removal, conducted at a stirring speed of 400 rpm with a particle size of 100 mesh, is presented in Figure 5 which shows that as the dosage of BNZ adsorbent increases, the percentage of ammonium removal also increases, with 1, 3, and 5 grams yielding 10.91, 49.09, and 70.13% removal, respectively. Theoretically, when the adsorbent dosage is increased, the potential for ammonium ions to interact with the active sites of BNZ becomes more significant, resulting in more ion exchange occurring between ammonium and the active sites of BNZ.

Referring to Figure 5, the larger the mass of adsorbent added, the greater the number of

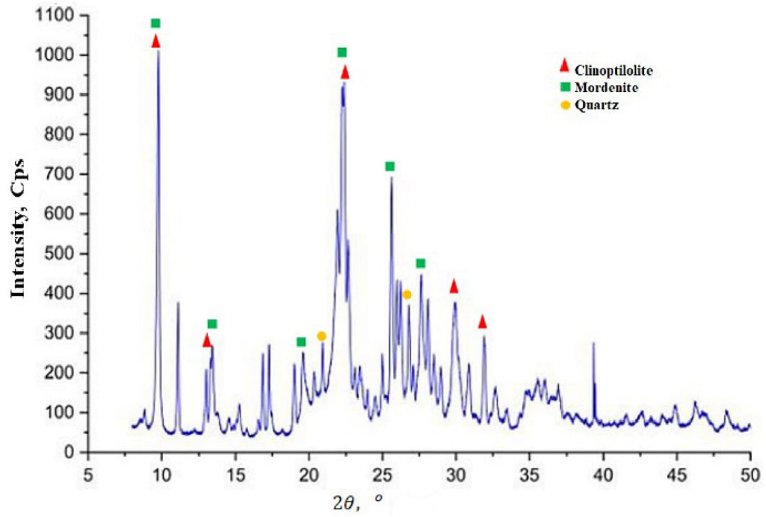

Figure 4. XRD test results of BNZ adsorbent

adsorbent particles interacting with ammonium ions, and the larger the total contact surface area between BNZ and ammonium ions. (Mamman et al., 2024). As a result, the mass transfer rate of ammonium ions increases (Figure 9). These results are similar to previous studies conducted by Ahmad et al. (2023) and Alsharief et al. (2024). The results of Ahmed et al. (2023) showed that adsorbent doses of 0.25–2.5 g/L increased the removal percentage of Cu^{2+} from 30 to 95%. Meanwhile, the results of Alsharief et al. (2024) showed that using adsorbent doses of 0.02–0.2 grams, the removal percentage of food azorubine E122 dye increased from 56.6 to 98.2%.

Effect of adsorbent particle size

Mesh is the number of holes per unit area in in^2, so the more significant the mesh value, the smaller the holes in the sieve or filter. Therefore, the order of BNZ adsorbent particle sizes from most significant to most minor is 40, 60, and 100 mesh. The study's results on the effect of particle size presented in Figure 5 show that the smaller the particle size (more significant mesh value), the greater the percentage of ammonium removal achieved. In sequence, for BNZ adsorbent sizes of 40, 60, and 100 mesh, the ammonium removal percentages obtained were 53.08, 66.38, and 70.13%. According to Lawal et al. (2024), the smaller the adsorbent particle size, the more significant the increase in ion exchange between the compound and the adsorbent, which is very relevant when linked to Equations 4–10.

Thus, based on the phenomenon in Figure 6, it is found that the smaller the adsorbent particle size, the larger the internal mass transfer constant (k) value Equations 5–7 will be, resulting in a higher adsorption rate in the system (Equations 4 and 10). The impact is that the ion exchange between ammonium and the active sites of the BNZ adsorbent also becomes more significant. The results of observations on the effect of particle size on removal percentage in the adsorption process from several references are presented in Table 2, which shows that the results of this study have a similar tendency to those of the existing references.

Effect of stirring speed on ammonium removal

The effect of stirring speed on ammonium removal, performed with a particle size of 100 mesh and an adsorbent mass of 5 grams, is presented in Figure 7.

Figure 7 shows that when the stirring speed is increased from 400 to 600 rpm, the ammonium removal percentage decreased from 70.13 to 52.21%. According to basic concepts, stirring speed should reduce external resistance in the external diffusion process through a film layer (Figure 2) and Equation 3, thus increasing the mass transfer rate. However, referring to Equations 5 and 6 to Equation 4, this phenomenon can potentially occur, where increasing the stirring speed given to the system can have the opposite effect (decrease in mass transfer rate and decrease in ammonium removal percentage). When the adsorbent particle size is too small at a certain speed, it can cause the Reynolds number of the adsorbent particles to be very small (< 1 and ≈ 0). In this condition, stagnation of the adsorbent particle movement will occur. Stagnation of particle movement

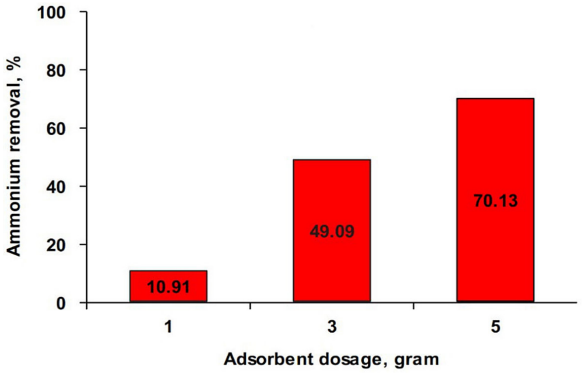

Figure 5. Effect of adsorbent dosage on ammonium removal conducted at a stirring speed of 400 rpm and particle size of 100 mesh

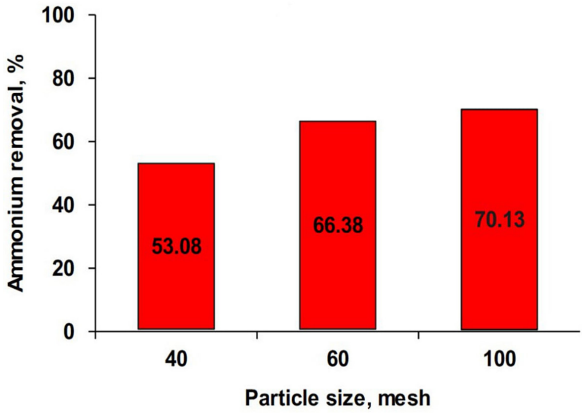

Figure 6. Effect of adsorbent particle size on ammonium removal conducted at a stirring speed of 400 rpm and adsorbent dose of 5 grams

Table 2. Results of observations on the effect of particle size on removal percentage in adsorption processes

Particle size	Removal: compound ion	Reference
213 µm–< 106 µm	± 95 mg/g to 130 mg/g (mg methylene blue/coconut coir dust/ adsorbent)	Al Ashik et al., 2023
200 µm – 30 µm	4.5×10^{-2} to 6×10^{-2} mmol/l methylene blue using carbon adsorbent	Bordun et al., 2023
105 µm – < 63 µm	20% to 36% methylene orange using orange peels adsorbent	Lawal et al., 2024
40–100 mesh (0.420–0.149 mm)	53.08 to 70.13%	This research

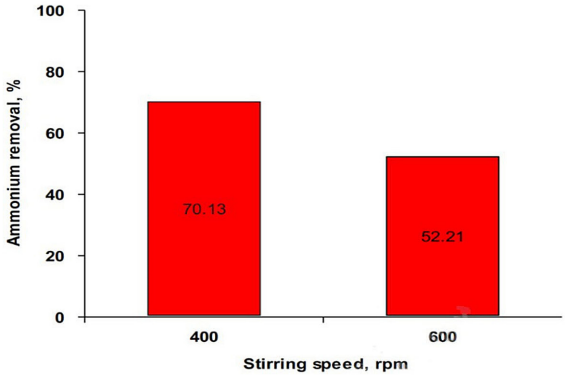

Figure 7. Effect of stirring speed on ammonium removal conducted at a particle size of 100 mesh and adsorbent mass of 5 grams

results in the Sherwood number (sh) value being 2 (Equation 6), and as a result, the sh value decreases, causing the k values (Equation 5) also to decrease. This condition causes the mass transfer rate of ammonium molecules to the adsorbent particles to decrease (Equation 4 and 10). A similar phenomenon was also experienced by Merrad et al. (2023) in the adsorption process of malachite green (MG) using Activated Carbon from Walnut Shells (ACWS) as the adsorbent with a relatively small adsorbent particle size of ± 0.045 mm, conducted in the stirring speed range of 150–450 rpm. When the stirring speed was increased from 150 to 300 rpm, the MG removal percentage increased significantly from 179 to 190 mg/g. When increased again from 300 to 400 rpm, the adsorption increased slightly to 192 mg/g. However, when the speed was increased to 450 rpm, MG removal decreased to below 190 mg/g. Different results were obtained by Chrachmy et al. (2024) for the same adsorption process, which was malachite green (MG), using clay as the adsorbent, which notably has a larger size. When the speed was increased to 750 rpm, it still experienced an increase, initially from 42.68 mg/g (250 rpm) to 43.17 mg/g at 750 rpm. The phenomenon in this study and its comparison with references show that the stirring speed given to the adsorption system has a maximum point for a specific adsorbent size. When it exceeds the maximum point, the opposite occurs, resulting in a decrease in the removal percentage of the compound.

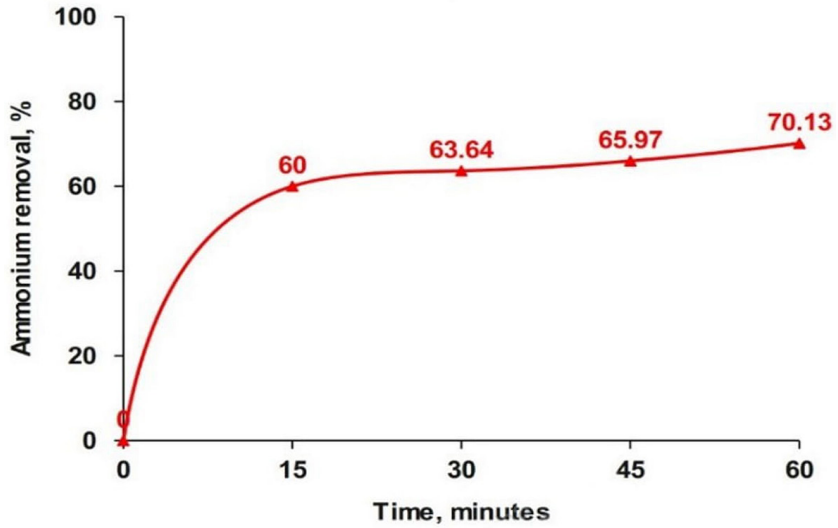

Figure 8. Effect of adsorption time on ammonium removal conducted at a particle size of 100 mesh, adsorbent mass of 5 grams, and stirring speed of 400 rpm

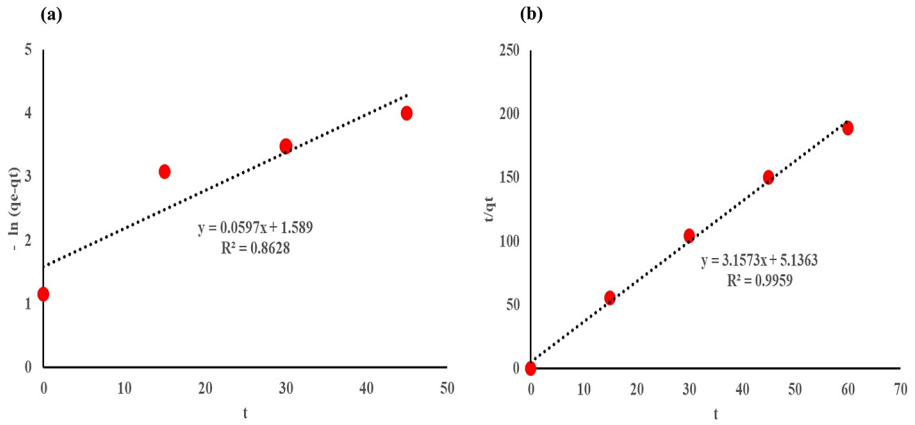

Figure 9. Adsorption kinetics of natural zeolite for ammonium removal (a) the first-order, (b) the second-order

Effect of adsorption time on ammonium removal

To examine the adsorption process trend in this study, a more detailed observation was conducted over 15–60 minutes under the best conditions: particle size of 100 mesh, adsorbent mass of 5 grams, and stirring speed of 400 rpm. As shown in Figure 8, the fastest ammonium adsorption occurred in the first 15 minutes, with an ammonium removal percentage of 60%. After 15 minutes of adsorption, the process continued but slowed down, increasing from 60% to 63.64%, 65.97% and 70.13% for 15, 30, 45, and 60 minutes, respectively. This phenomenon in the study is logical, as the diffusivity rate is a function of concentration, so when the concentration is still high, the diffusivity rate is also high (see Equation 3). Similar results were also experienced by Liu et al. (2024) in the ammonium adsorption process using *granular hydrogel composites* as adsorbents, where the ammonium adsorption process increased but experienced a slowdown.

Validation of adsorption kinetics of natural zeolite for ammonium removal

The adsorption kinetics of natural zeolite for ammonium removal are presented in Figure 9, which shows that the curve fitting of the model for the second-order (Figure 9b) is better compared to the first-order (Figure 9a), where the R^2 value for the second-order is closer to 1 than the first-order, with values of 0.8628 for the first-order and 0.9959 for the second-order. Therefore, the second-order adsorption kinetics model is the mathematical model that adequately describes the adsorption using Bayah, Indonesia, natural zeolite adsorbent. In similar studies by Kurniawan et al. (2020) and Zhou et al. (2024) on ammonium adsorption using zeolite, it was also shown that the pseudo-homogeneous second-order adsorption kinetics model is the best for describing the ammonium adsorption process.

Referring to the best mathematical model (the second-order) in Figure 9 (b) with qe = 1/ 3.1573 = 0.3167 mg/g, and $\frac{1}{k_2 q_e^2}$ = 5.1363, the adsorption rate constant (k_2) is obtained as 1.940802 g/mg·min. Research by Kurniawan et al. (2020) and Zhou et al. (2024) obtained k_2 values of -0.28 dan 0.0654 g/mg·min, respectively. Thus, the rate of this study is much faster than that of both. This is possible because Kurniawan et al. (2020) study was conducted without stirring, and Zhou et al. (2024) study was done by stirring at only 150 rpm, whereas in this study it was conducted with stirring at 400 rpm. Therefore, the stirring factor is suspected to have a significant role in accelerating the adsorption process, as long as the stirring process does not cause stagnation of adsorbent movement, as previously explained (see Figure 7).

CONCLUSIONS

Based on the number of peaks that appear, BNZ is dominated by mordenite and clinoptilolite types, with a small amount of Quartz. Increasing the adsorbent dose from 1–5 grams, reducing the adsorbent size from 40 mesh to 100 mesh, and extending the contact time from 0–60 minutes positively impact the ammonium adsorption process (% ammonium removal increases). Conversely, increasing the stirring speed from 400 to

600 rpm, intended to accelerate the diffusion process for better adsorption, has a negative impact (% ammonium removal decreases). The optimal conditions in this study were obtained at a mass of 5 grams, a zeolite size of 100 mesh, and a stirring speed of 400 rpm for 60 minutes, with an ammonium removal percentage of 70.13%. The ammonium adsorption process using natural zeolite adsorbent from Bayah, Indonesia, can be described using the pseudo-homogeneous second-order adsorption kinetics model with a suitable validation level (referring to the data-model curve fitting) with an R^2 value of 0.9959, which close to 1, and adsorption rate constant of 1.940802 g/mg·min. Further studies need to be conducted by integrating other influential factors in the adsorption process, such as activating BNZ before use to increase its porosity and active sites, thus improving the ammonium adsorption process in wastewater from the tofu industry. The hope is that the wastewater from the tofu industry can eventually meet the required waste quality standards.

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