IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 5 (2026) 177-189
https://publisher.uthm.edu.my/ojs/index.php/ijie

# Exploring The Adsorption of Nutrients in Industrial Wastewater Using Zeolite

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DOI: https://doi.org/10.30880/ijie.2026.18.05.016

**Article Info**

Received: 3 October 2025
Accepted: 18 June 2026
Available online: 4 August 2026

**Keywords**

Industrial wastewater, batch adsorption, zeolite, nutrients removal, isotherm, kinetic study

**Abstract**

Industrial wastewater often contains excess nutrients that can trigger eutrophication if discharged untreated. Zeolite, with its distinct physical and chemical properties, is widely used in wastewater treatment. This work focused on investigating the morphological alterations on the zeolite surface, optimising adsorption operational parameters, and evaluating the adsorption behaviour of ammonium, nitrate, and phosphorus through isotherm and kinetic models. Zeolite was characterised by Scanning Electron Microscopy (SEM), and batch-mode adsorption experiments were operated with varying wastewater percentages (10 - 100% v/v), zeolite dosages (0.4 g - 1.2 g), pH (4 - 9), and contact times (5 - 120 minutes). SEM analysis showed that the initially porous, rough zeolite surface became smoother and less porous after adsorption, confirming nutrient attachment to the zeolite surface. Optimal nutrient removal was achieved at 10% (v/v) wastewater, 1.2 g of zeolite, pH 7, and a 120-minute contact time with agitation at 80 rpm, achieving efficiencies of 32% for ammonium, 67% for nitrate, and 59% for phosphorus. Isotherm analysis showed that ammonium adsorption was better represented by the Freundlich model, nitrate aligned strongly with the Langmuir model, and phosphorus exhibited weak agreement with both models. Also, ammonium and nitrate followed the pseudo-second-order kinetic model, whereas phosphorus was better described by the pseudo-first-order model. The adsorption capabilities of zeolite for nutrient removal were successfully explored, demonstrating its potential as a sustainable treatment option.

## 1. Introduction

Wastewater generation has been steadily increasing due to rapid industrialisation and urban development. Wastewater from domestic, agricultural, and some industrial sectors, such as food, dairy, and paper and pulp, contains significant amounts of nutrients [1], [2]. Numerous nutrients, including phosphorus, nitrogen, potassium, ammonium, and sulphur, are present in industrial wastewater [3], [4]. The continuous discharge of nutrient-rich effluents into receiving water bodies leads to excessive enrichment, particularly in nitrogen and phosphorus. Such inputs stimulate excessive algal blooms and aquatic plant proliferation, a phenomenon commonly referred to as eutrophication [5]. This process severely disrupts aquatic ecosystems by depleting dissolved oxygen, altering pH and other water chemistry parameters, reducing light penetration into deeper layers, and, in some cases, promoting the release of harmful cyanotoxins [6]. Prolonged eutrophication not only threatens aquatic biodiversity and disrupts microbial balance but also diminishes overall water quality. Beyond ecological degradation, these conditions pose direct risks to public health and undermine economic activities that rely on clean, safe water resources, including fisheries, recreational uses, tourism, and the production of potable water [5], [7].

Wastewater treatment is very important for removing excess nutrients before wastewater is released into water bodies. Various treatments have been applied to remove nutrients from industrial wastewater. These treatments include anaerobic treatment, adsorption, rotating biological contactors, coagulation, flocculation, sedimentation, filtration, phytoremediation and biological nutrient removal [8], [9]. The best method for removing nutrients from industrial wastewater is selected based on key factors, including cost, nutrient concentration, and removal efficiency. The most popular treatment is adsorption because of its cost-effectiveness, process flexibility and design flexibility. The microporous structure of the adsorbent materials plays a major role in the adsorption process. These materials can be natural, synthetic, or modified to enhance their adsorption capacities. Some examples of adsorbents for nutrient removal include zeolite, clay minerals, alumina, chitosan, activated carbon, and shells [10]-[14]. Among these adsorbents, zeolites have advantages over others due to their permeability, adsorption, and catalytic properties [15]. Zeolites have a porous structure and can adsorb a variety of sorbates, including insecticides, polar and nonpolar inorganic and organic compounds [16].

Unlike many previous studies that investigated adsorption using synthetic solutions or targeted only a single nutrient, this work examines the simultaneous removal of ammonium, nitrate, and phosphorus from real industrial wastewater using natural zeolite. The contribution of this study is the identification of optimal operational parameters for nutrient adsorption using zeolite, providing practical evidence of its applicability in treating nutrient-rich industrial wastewater. This research aims (i) to investigate the morphological alterations on the zeolite surface post-treatment, (ii) to optimise adsorption operational variables including percentage of wastewater, dosage of zeolite, solution pH and contact time, and (iii) to evaluate the adsorption behaviour of ammonium, nitrate and phosphorus using isotherm and kinetic models.

## 2. Materials and Methods

### 2.1 Pre-Treatment of Zeolite

The zeolite used in this work was purchased from CPR Feed Sdn. Bhd. Prior to application, it was ground and sieved to obtain particles of 150 μm. The material was then oven-dried at 60°C for 8 hours to remove residual moisture [17].

### 2.2 Sampling of Industrial Wastewater

Industrial wastewater was collected from the ethanol production factory in Bukit Keteri, Perlis. About 15.0 L of wastewater was collected using an HDPE bottle. Next, the collected wastewater was stored in a chiller at 4°C until further use.

### 2.3 Characterisation of Zeolite

The morphology of the zeolite surface was examined using Scanning Electron Microscopy (SEM) before and after the treatment. SEM utilised a focused electron beam to capture detailed images of the sample's surface structure. The analysis was conducted using a JEOL JSM-6010LV SEM, operating at acceleration voltages ranging from 0.5 to 20 kV.

### 2.4 Optimisation of Zeolite-Adsorption Operating Parameters

The study investigated nutrient adsorption using zeolite via a batch-method experiment, optimising operational parameters such as wastewater percentage, zeolite dosage, pH, and contact time. Each experiment used 100 mL of wastewater sample, agitated at 80 rpm on an orbital shaker [18]. The optimisation began by varying the

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wastewater percentage (10 to 100% v/v) while keeping other parameters constant. Next, zeolite dosage was optimised within the range of 0.4 to 1.2 g. Subsequently, pH was adjusted from 4 to 9 using the optimised dosage and wastewater percentage. Finally, contact time was varied between 5 and 120 minutes under the previously optimised conditions. Table 1 summarises these operational conditions for zeolite adsorption in nutrient removal. Nutrient concentrations were measured using a DR3900 spectrophotometer. The ammonium concentration was determined using the Nessler method (HACH Method 8038), nitrate using the Cadmium Reduction method (HACH Method 8039) and phosphorus using the PhosVer 3 (Ascorbic Acid) method (HACH Method 8048).

**Table 1** *Operational conditions of zeolite-adsorption for nutrient removal*

| Parameter | Operational conditions | | | |
|---|---|---|---|---|
| | Percentage of wastewater (% v/v) | Dosage (g) | pH | Contact time (minute) |
| Percentage of wastewater | 10, 25, 50, 75, 100 | 1.0 | 7 | 60 |
| Dosage | 10 | 0.4, 0.6, 0.8, 1.0, 1.2 | 7 | 60 |
| pH | 10 | 1.2 | 4, 6, 7, 8, 9 | 60 |
| Contact time | 10 | 1.2 | 7 | 5, 20, 40, 60, 120 |

## 2.5 Adsorption Assessment

The efficiency of nutrient removal by zeolite was determined using Eqn. (1).

$$\text{Percentage of removal } (\%) = \frac{C_i - C_f}{C_i} \times 100\% \quad (1)$$

where $C_i$ represents the nutrient concentration before treatment (mg/L), and $C_f$ denotes the nutrient concentration after treatment (mg/L).

## 2.6 Isotherm and Kinetic Analysis Methods

Langmuir and the Freundlich isotherm models, together with pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic approaches, were applied to describe the adsorption behaviour of ammonium, nitrate, and phosphorus onto zeolite. Table 2 presents the linear form of isotherm and kinetic models, along with their parameters and descriptions.

**Table 2** *Linear equations for isotherm and kinetic models*

| Model | Linear equation | Description | References |
|---|---|---|---|
| Langmuir isotherm | $\frac{C_e}{q_e} = \frac{C_e}{q_{max}} + \frac{1}{bq_{max}}$ | $C_e$ = nutrient concentration at equilibrium (mg/L), $q_e$ = amount adsorbed on zeolite at equilibrium (mg/g), $q_{max}$ = maximum adsorption capacity (mg/g), $b$ = Langmuir equilibrium constant (L/mg) | [19] |
| Freundlich isotherm | $\log q_e = \log K_F + \frac{1}{n} \log C_e$ | $K_F$ = Freundlich constant (mg/g) $(L/mg)^{1/n}$, $n$ = adsorption intensity | [20] |
| Pseudo-first-order (PFO) kinetics | $\log (q_e - q_t) = \log q_e - \frac{k_1}{2.303} t$ | $q_t$ = amount adsorbed on zeolite at time $t$ (mg/g), $q_e$ = equilibrium adsorption capacity (mg/g), $k_1$ = rate constant of PFO (1/min) | [21] |
| Pseudo-second-order (PSO) kinetics | $\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$ | $k_2$ = rate constant of PSO (g/mg·min) | [22] |

## 3. Results and Discussions

### 3.1 Characterisation of Zeolite

Fig. 1 shows the morphological variations on the zeolite surface. Prior to adsorption (see Fig. 1(a)), the zeolite surface exhibited a relatively rough, heterogeneous texture with distinct pores, fissures, and cavities. These morphological features are consistent with the zeolite's highly porous aluminosilicate framework, which facilitates ion exchange and provides abundant active sites for nutrient binding. The sharp edges and well-defined voids indicate the presence of open adsorption channels that are accessible to ammonium, nitrate, and phosphorus species in solution.

After adsorption (see Fig. 1(b)), notable changes in the surface morphology were observed. The zeolite surface appeared more compact, with many pores and cavities either partially blocked or completely covered by adsorbed material. Compared with the surface before adsorption, the zeolite became less porous and exhibited smoother textures in certain areas, suggesting the deposition of nutrient ions onto the active sites. The reduction in visible voids further suggests that the internal channels of the zeolite framework were occupied during adsorption. In addition to nutrient attachment, these changes may also be attributed to impurities present in the wastewater and the mechanical agitation during oscillation, which likely caused minor abrasion and damage to the edges and corners of the zeolite particles [23].

Comparable SEM features were highlighted by Nguyen et al. [24], who reported that the zeolite surface became less rough after the adsorption of ammonium ions. This strengthens the evidence that surface smoothing and pore filling are reliable indicators of nutrient uptake. This study revealed clear morphological alterations that validate the attachment of nutrients to the zeolite surface and are consistent with earlier reports. Overall, the SEM analysis highlights the transition from a porous, open structure before adsorption to a more compact, filled morphology after adsorption, thereby confirming nutrient attachment to the zeolite surface.

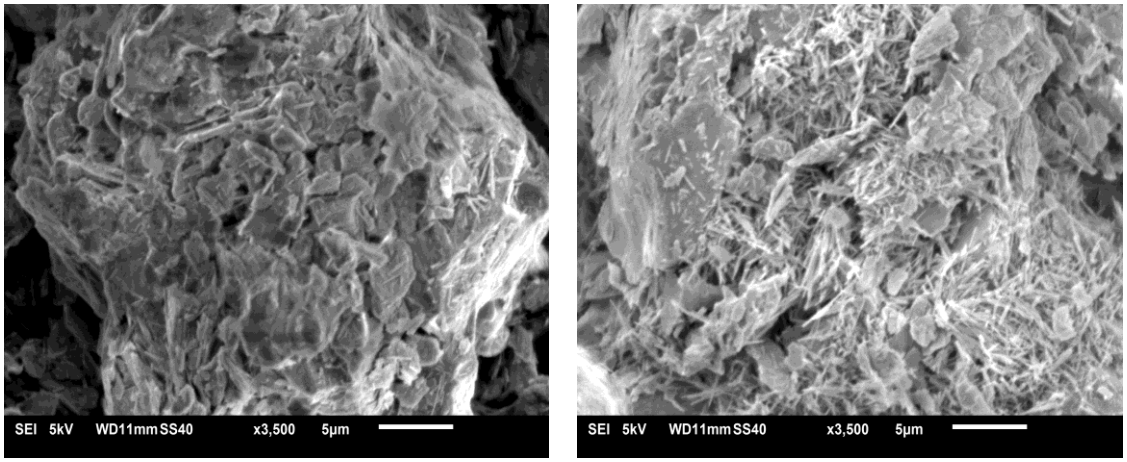


**Fig. 1** *SEM micrographs of zeolite (a) Prior to adsorption; (b) Post-adsorption*

### 3.2 Optimisation of Operational Parameters for Zeolite-Based Adsorption

Operational parameters, including the percentage of wastewater, zeolite dosage, pH, and contact time, were optimised to establish the best conditions for nutrient removal via zeolite adsorption.

#### 3.2.1 Percentage of Wastewater

Fig. 2 illustrates the percentage removal of ammonium, nitrate, and phosphorus using zeolite at different wastewater concentrations. The percentage removal of ammonium, nitrate, and phosphorus generally decreased as the wastewater concentration increased from 10% to 100% (v/v). Specifically, ammonium removal decreased from 44% to 27% as the wastewater fraction increased from 10% to 100% (v/v). Nitrate removal showed a similar trend, declining from 80% to 60%. Phosphorus removal was also reduced, with the percentage removal decreasing from 65% to 26% as the wastewater percentage increased from 10% to 100% (v/v). Among all tested conditions, the 10% (v/v) wastewater concentration exhibited the highest removal efficiency for all three nutrients, indicating that a lower wastewater concentration is more favourable for effective zeolite adsorption. This suggests that 10% (v/v) percentage wastewater achieved the highest removal efficiency in the adsorption process, achieving 44% for ammonium, 80% for nitrate, and 65% for phosphorus.

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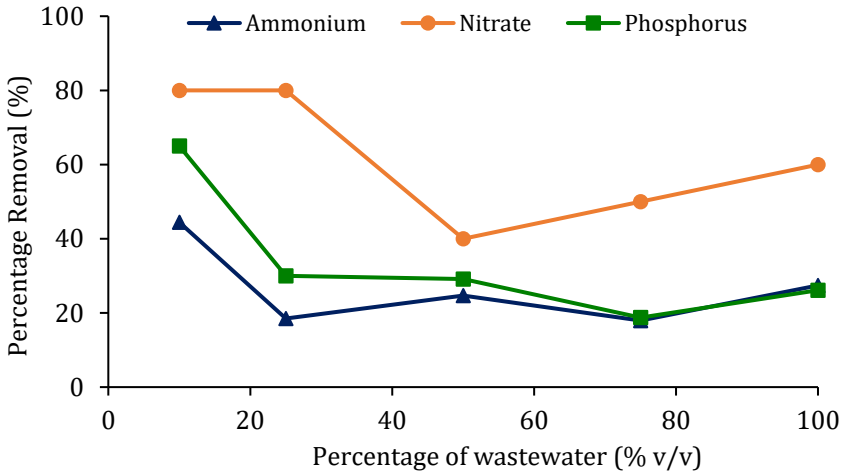


**Fig. 2** *Percentage removal of ammonium, nitrate and phosphorus at different percentages of wastewater (1.0 g zeolite dosage, pH 7 and 60 minutes contact time at 80 rpm)*

This finding suggests that lower wastewater concentrations provide more favourable conditions for nutrient adsorption using zeolite. At lower concentrations, the competition between nutrient ions for available adsorption sites on the zeolite surface is reduced, allowing for more effective interaction between the adsorbent and adsorbate [25]. Additionally, lower concentrations likely prevent rapid saturation of active sites and promote a higher mass-transfer rate by increasing the concentration gradient. The diluted wastewater also reduces the presence of interfering substances that may block adsorption sites, enhancing the overall effectiveness of the adsorption process. This trend supports the principle that adsorption efficiency generally decreases as contaminant loading increases when the adsorbent dosage remains constant.

However, when the wastewater percentage increased from 75% to 100% (v/v), a higher initial concentration increased the driving force for mass transfer, thereby accelerating the migration of nutrient ions from the bulk solution to the zeolite surface [26]. This supports the observation that when the wastewater concentration increased up to 100% (v/v), the percentage removal of most nutrients showed a slight increase after previously declining. This unexpected rise may be attributed to changes in adsorption dynamics at higher contaminant loading, such as increased ion mobility or delayed equilibrium, which could enhance interactions between nutrients and the zeolite surface. The percentage removal of nutrients was also directly affected by the characteristics of the industrial wastewater, which likely contained high nutrient concentrations from manufacturing discharges. The 10% (v/v) wastewater concentration achieved the greatest nutrient removal, suggesting that this concentration provided the best adsorption conditions. Therefore, the optimal wastewater concentration was 10% (v/v), which was selected as the next parameter for the adsorption operation. Similar to Safie & Zahrim [25] and Abdulredha et al. [27], this study found that lower wastewater concentrations led to higher adsorption efficiency, as fewer competing ions enabled more effective interactions between nutrients and zeolite.

### 3.2.2 Dosage of Zeolite

The percentages of removal of ammonium, nitrate and phosphorus were significantly influenced by the dosage of zeolite, as shown in Fig. 3. Overall, nutrient removal efficiencies increased with higher zeolite dosages, although some fluctuations were observed. For ammonium, the percentage removal started at 24% (0.4 g), dropped to 13% (0.6 g), and then increased gradually to 37% at 1.2 g. However, the percentage removal of nitrate was high at 0.4 g (75%), decreased to 33% at 0.6 g, and then increased steadily, reaching 80% at 1.2 g. Meanwhile, phosphorus shows that the percentage removal increased from 14% (0.4 g) to 55% (0.8 g), decreased to 15% at 1.0 g, and then increased sharply to 73% at 1.2 g. The optimum dosage was identified as 1.2 g, yielding the highest removal percentages for all three nutrients: ammonium (37%), nitrate (80%), and phosphorus (73%).

This study reveals that increasing the zeolite dosage from 0.4 g to 1.2 g significantly enhances the removal of ammonium, nitrate, and phosphorus from industrial wastewater. The results show that nutrient removal efficiency generally improved with increasing zeolite dosage. The highest percentage removal for all three nutrients was recorded at 1.2 g, indicating that a higher dosage provides more active sites and a larger surface area available on the zeolite's surface for adsorption [27]. At lower dosages, the limited surface area and active sites may have restricted the interaction between the adsorbent and nutrient ions, resulting in lower removal percentages. As the dosage increased, the enhanced adsorbent-to-adsorbate ratio facilitated greater contact and

improved adsorption. However, some fluctuations in removal were observed at intermediate dosages, which may be attributed to temporary site saturation or competition among ions. Overall, the findings suggest that 1.2 g of zeolite was the most effective dosage under the tested conditions. Therefore, 1.2 g of zeolite was chosen for the next adsorption operation parameter optimisation using zeolite for nutrient removal. The trend of increasing nutrient removal with higher adsorbent dosage is consistent with Nur Afikah [28] and Ram et al. [29], who demonstrated that higher zeolite dosage increases surface area and the availability of adsorption sites.

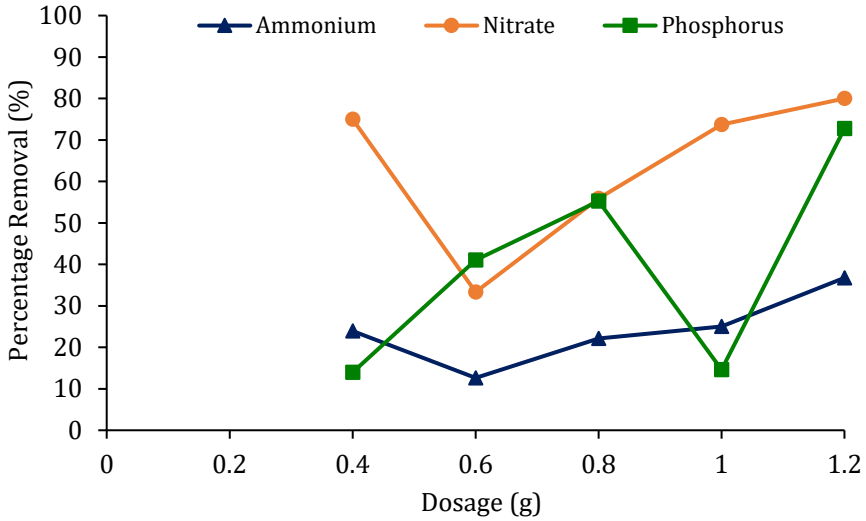


**Fig. 3** *Percentage removal of ammonium, nitrate and phosphorus at different dosages of zeolite (10% v/v of the percentage of wastewater, pH 7 and 60 minutes contact time at 80 rpm)*

### 3.2.3 pH

The percentage removal of all three nutrients using zeolite was influenced by changes in pH, as shown in Fig. 4. For ammonium, the percentage removal increased steadily from 14% at pH 4 to a maximum of 53% at pH 7. However, beyond this point, efficiency dropped sharply to 10% at pH 8, then increased slightly to 17% at pH 9. Similarly, nitrate removal showed an overall increasing trend up to pH 7, starting at 27% at pH 4, rising to 40% at pH 7, then declining to 26% at pH 8, and increasing again to 36% at pH 9. For phosphorus, the removal efficiency was initially 40% at pH 4, decreased slightly to 35% at pH 6, and peaked at 44% at pH 7. After reaching its optimum, the removal dropped to 19% at pH 9. Based on the results, pH 7 was identified as the optimum condition for nutrient removal using zeolite. At this pH, the highest removal efficiencies were observed for ammonium (53%) and phosphorus (44%), while nitrate showed a relatively high removal of 40%. These values indicate that a neutral pH provides the most favourable environment for effective adsorption of all three nutrients.

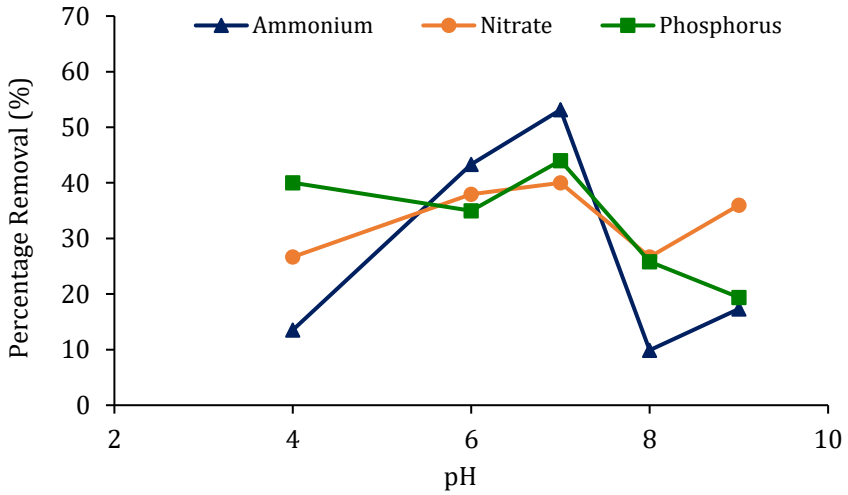


**Fig. 4** *Percentage removal of ammonium, nitrate and phosphorus at different pH (10% v/v of percentage of wastewater, 1.2 g zeolite dosage and 60 minutes contact time at 80 rpm)*

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The adsorption performance of zeolite is strongly influenced by the pH of the solution, as it controls the surface charge of the adsorbent as well as the ionic speciation of nutrients. Under acidic conditions, the zeolite surface tends to become positively charged, thereby limiting cation uptake due to electrostatic repulsion and competition with excess hydrogen ions [30]. Conversely, at higher pH levels, the zeolite surface tends to become negatively charged, which may enhance the adsorption of cationic species but may also increase competition from hydroxide ions [31]. Neutral pH conditions generally provide a more balanced environment where both the adsorbent surface and the nutrient ions are in a favourable state for interaction. This has been reported in previous studies, where zeolite exhibited improved adsorption performance at neutral pH due to optimal electrostatic attraction and minimal interference from competing ions. Moreover, the efficiency of nutrient removal at different pH levels may also be influenced by the solubility and ionic forms of the nutrients involved. For instance, phosphorus and ammonium exist in multiple species depending on pH, and these forms interact differently with the zeolite surface [25].

The most common pH values for zeolite-based adsorption in nutrient removal were slightly acidic or near neutral, at pH 6 and 7. Comparable outcomes have been documented by Ram et al. [29] and Nasir et al. [31]. The sorption capacity decreased at very low pH levels due to competition with hydrogen ions, making it challenging to adsorb ammonium in wastewater [32]. Also, the adsorption capability decreased at higher pH values, specifically at pH 8 and 9 [33]. Therefore, a pH of 7 was chosen to optimise the adsorption operating parameters for the next experiment.

### 3.2.4 Contact Time

Fig. 5 presents the effect of contact times on the percentage removal of ammonium, nitrate and phosphorus using zeolite. The removal percentages of ammonium, nitrate, and phosphorus by zeolite increased with contact time over 5-120 minutes. For ammonium, the removal percentage increased steadily from 20% at 5 minutes to 32% at 120 minutes. Phosphorus showed a similar progressive pattern, rising from 30% to 59% over the same contact period. Nitrate, however, displayed a different trend. Its removal percentage decreased from 42% at 5 minutes to 22% at 60 minutes, then increased sharply to 67% at 120 minutes.

The gradual increase in ammonium and phosphorus removal suggests that zeolite has a consistent affinity for both ions, with adsorption progressing toward equilibrium. The slower rate of increase at longer contact times indicates a gradual saturation of active sites on the zeolite surface. This behaviour is consistent with the general adsorption mechanism, which typically involves two stages: (i) a rapid initial uptake due to abundant available surface sites, and (ii) a slower phase dominated by intraparticle diffusion as equilibrium is approached [34], [35]. The unusual behaviour of nitrate, showing an initial decline followed by a sharp increase, can be explained by ion competition and adsorption dynamics. During the early stage, nitrate ions may have competed with other ions in the wastewater for adsorption sites or undergone partial desorption. With extended contact, however, nitrate molecules had sufficient time to diffuse into the zeolite's internal pores, resulting in improved uptake at later stages.

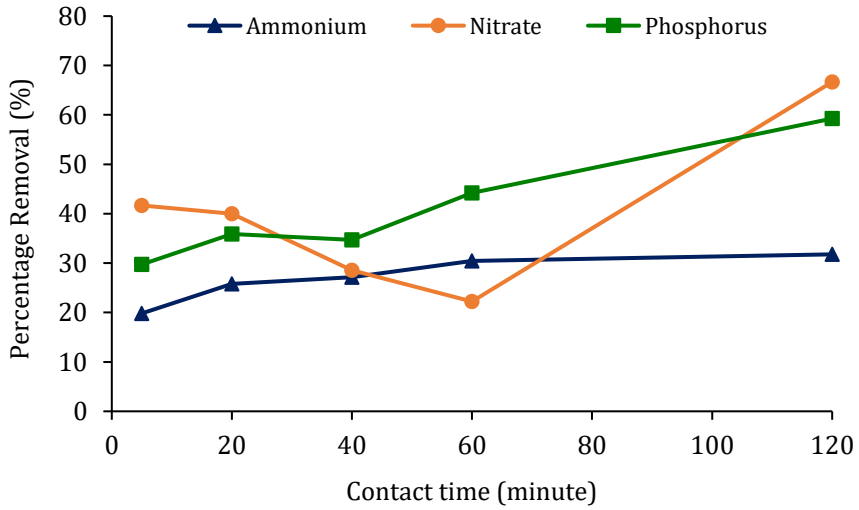


**Fig. 5** *Percentage removal of ammonium, nitrate and phosphorus at different contact times (10% v/v of percentage of wastewater, 1.2 g zeolite dosage and pH 7 at 80 rpm)*

The optimal contact time for the zeolite-based adsorption process was determined to be 120 minutes for effective nutrient removal. This finding aligns with Abdulredha et al. [27], Abdelhay et al. [36] and Widiastuti et

al. [37], who observed that nutrient removal increases with longer contact time until equilibrium is reached, supporting the 120 minutes identified in this study.

## 3.3 Adsorption-Isotherm Evaluation

The equilibrium data for the adsorption of ammonium, nitrate, and phosphorus were interpreted using the Langmuir and the Freundlich equations to evaluate the interactions between nutrients and zeolite. Langmuir theory is based on monolayer adsorption at homogeneous sites, whereas the Freundlich theory describes multilayer adsorption on a heterogeneous surface [37].

The linearised Langmuir plots of $C_e/q_e$ versus $C_e$ for ammonium, nitrate and phosphorus adsorption on zeolite are shown in Fig. 6. Table 3 summarises the Langmuir isotherm parameters for adsorption on zeolite. For the Langmuir model, nitrate adsorption showed the best fit (coefficient of determination, $R^2$ = 0.9323), confirming a monolayer adsorption mechanism with a maximum adsorption capacity ($q_{max}$) of 3.53 mg/g and a Langmuir constant ($b$) of 0.148 L/mg. In contrast, ammonium ($R^2$ = 0.0809) and phosphorus ($R^2$ = 0.2579) displayed weak correlations, indicating that their adsorption was not adequately explained by homogeneous monolayer behaviour. Ammonium adsorption was most likely controlled by ion-exchange interactions, whereas phosphorus uptake could occur through mechanisms such as surface complexation or precipitation.

The Freundlich model provided additional insights, as shown in Fig. 7 and Table 4. Nitrate again exhibited a reasonably good fit ($R^2$ = 0.7784, $n$ = 2.91), suggesting favourable adsorption (where $1/n < 1$) and a heterogeneous distribution of active sites [38]. Ammonium ($R^2$ = 0.6008, $n$ = 1.55) was more accurately represented by the Freundlich isotherm than the Langmuir, implying uptake on irregular surface sites with moderate binding strength. Phosphorus, however, showed poor correlation ($R^2$ = 0.1938, $n$ = 3.66), reflecting complex interactions that cannot be fully explained by either model alone. The relatively low $K_F$ values for ammonium (0.115) and phosphorus (0.239), compared with nitrate (0.886), further demonstrate that nitrate has a higher affinity for the zeolite surface.

Overall, the isotherm results suggest that nitrate removal was better described by the Langmuir than by the Freundlich model, highlighting the dominance of monolayer adsorption on homogeneous sites. Ammonium removal is better explained by the Freundlich model, consistent with ion exchange and heterogeneous adsorption processes, whereas phosphorus adsorption is only weakly represented by both models, suggesting that other mechanisms, such as surface complexation or precipitation, may dominate. This outcome aligns with earlier reports, in which ammonium removal by zeolite is governed by ion exchange [37], [39], whereas phosphorus adsorption often deviates from ideal isotherm models due to surface precipitation and multi-mechanistic pathways.

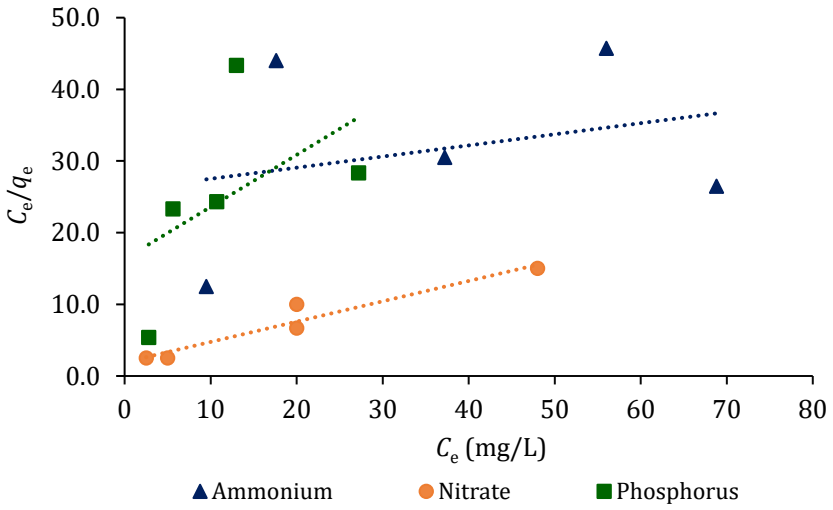


**Fig. 6** *Linearised Langmuir isotherm plots for ammonium, nitrate, and phosphorus adsorption onto zeolite*

**Table 3** *Langmuir isotherm parameters for ammonium, nitrate, and phosphorus adsorption onto zeolite*

| Parameter | Linear equation | $R^2$ | $q_{max}$ (mg/g) | $b$ (L/mg) |
|---|---|---|---|---|
| Ammonium | y = 0.1552x + 25.963 | 0.0809 | 6.44 | 0.006 |
| Nitrate | y = 0.2835x + 1.9181 | 0.9323 | 3.53 | 0.148 |
| Phosphorus | y = 0.7265x + 16.325 | 0.2579 | 1.38 | 0.045 |

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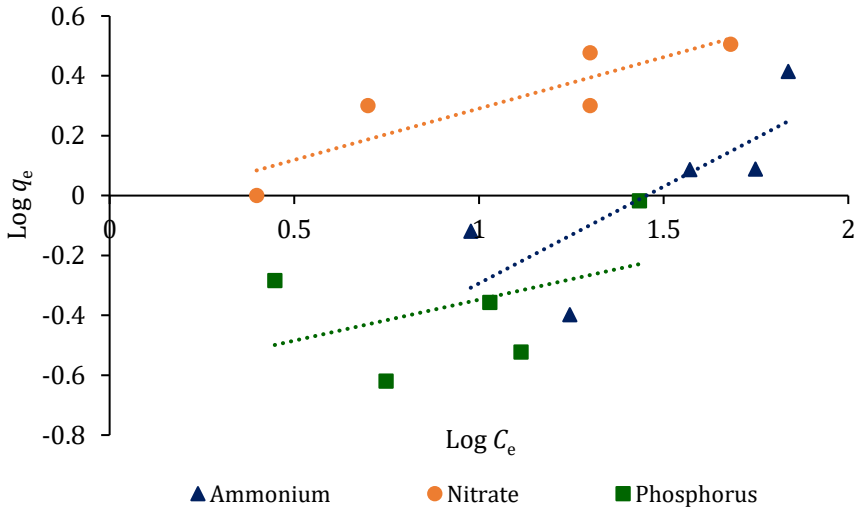


**Fig. 7** *Linearised Freundlich isotherm plots for ammonium, nitrate, and phosphorus adsorption onto zeolite*

**Table 4** *Freundlich isotherm parameters for the adsorption of ammonium, nitrate and phosphorus on zeolite*

| Nutrient | Linear equation | $R^2$ | $K_F$ (mg/g) (L/mg)$^{1/n}$ | $n$ | Adsorption nature |
|---|---|---|---|---|---|
| Ammonium | y = 0.647x – 0.9404 | 0.6008 | 0.115 | 1.55 | Favourable |
| Nitrate | y = 0.3434x – 0.0527 | 0.7784 | 0.886 | 2.91 | Favourable |
| Phosphorus | y = 0.2736x – 0.6214 | 0.1938 | 0.239 | 3.66 | Favourable, but poorly fitted |

## 3.4 Adsorption-Kinetic Evaluation

The kinetic behaviour of ammonium, nitrate and phosphorus adsorption onto zeolite was evaluated using pseudo-first-order (PFO) and pseudo-second-order (PSO) models. Fig. 8 and Fig. 9 present the respective linear plots, while Table 5 lists the kinetic modelling results for ammonium, nitrate, and phosphorus using the PFO and PSO equations.

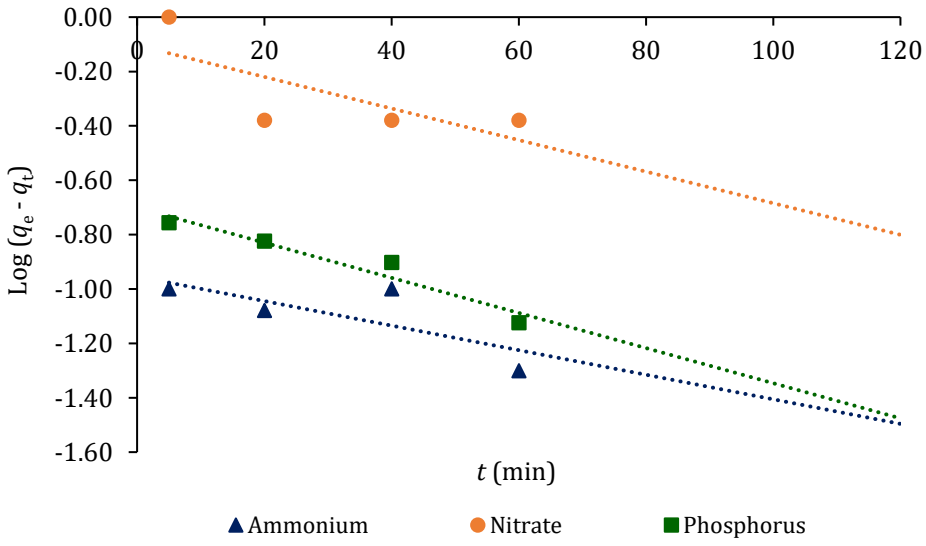


**Fig. 8** *Linearised PFO kinetic plots for ammonium, nitrate, and phosphorus adsorption onto zeolite*

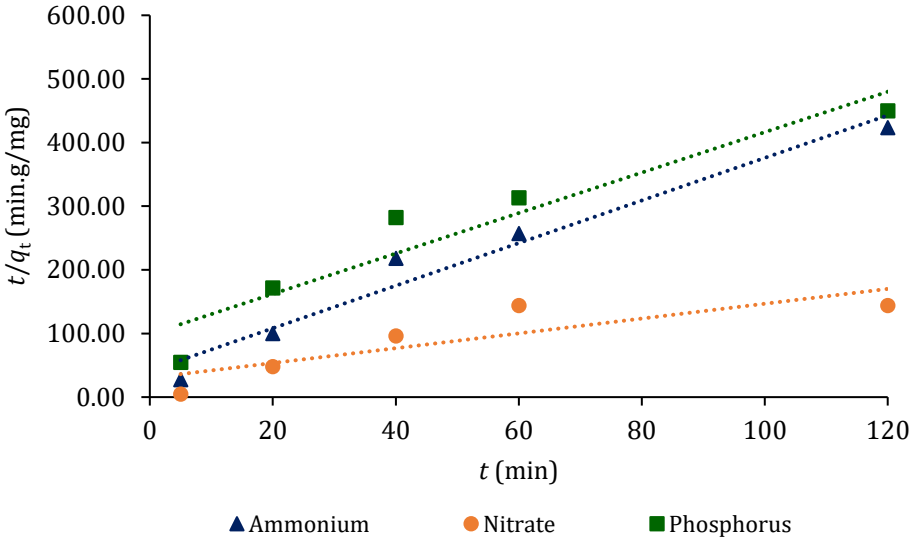


**Fig. 9** *Linearised PSO kinetic plots for ammonium, nitrate, and phosphorus adsorption onto zeolite*

**Table 5** *Kinetic modelling results for ammonium, nitrate and phosphorus using PFO and PSO equations*

| Nutrient | Model | $R^2$ | $q_{e,\,exp}$ (mg/g) | $q_{e,\,cal}$ (mg/g) | $k_1$ (1/min) | $k_2$ (g/mg. min) |
|---|---|---|---|---|---|---|
| Ammonium | PFO | 0.5773 | 0.283 | 0.111 | 0.0104 | - |
| | PSO | 0.9628 | 0.283 | 0.299 | - | 0.2713 |
| Nitrate | PFO | 0.5345 | 0.833 | 0.788 | 0.0134 | - |
| | PSO | 0.7323 | 0.833 | 0.859 | - | 0.0448 |
| Phosphorus | PFO | 0.9338 | 0.267 | 0.199 | 0.0150 | - |
| | PSO | 0.9065 | 0.267 | 0.315 | - | 0.1024 |

For ammonium, the PFO model yielded a moderate fit ($R^2$ = 0.5773) but underestimated the calculated uptake capacity ($q_{e,\,cal}$ = 0.111 mg/g) relative to the experimental equilibrium uptake capacity ($q_{e,\,exp}$ = 0.283 mg/g). In contrast, the PSO model yielded a very good correlation ($R^2$ = 0.9628), with $q_{e,\,cal}$ = 0.299 mg/g, closely matching the experimental value. The high agreement between calculated and experimental capacities indicates that ammonium adsorption on zeolite is best described by the PSO model, suggesting that the rate-limiting step involves chemisorption via valence forces or ion exchange at active sites.

For nitrate, the PFO model also showed a moderate fit ($R^2$ = 0.5345), whereas the PSO model provided a better fit ($R^2$ = 0.7323), though the correlation was lower than for ammonium. The calculated equilibrium capacity ($q_{e,\,cal}$ = 0.859 mg/g) was close to the experimental value ($q_{e,\,exp}$ = 0.833 mg/g), indicating that the PSO model is more appropriate for nitrate adsorption. The lower $R^2$ compared to ammonium suggests that nitrate adsorption may be influenced by additional mechanisms, such as diffusion into internal pores or weaker electrostatic interactions.

For phosphorus, both PFO and PSO models provided very good agreement with experimental data. The PFO model achieved a high correlation ($R^2$ = 0.9338), with $q_{e,\,cal}$ = 0.199 mg/g compared to $q_{e,\,exp}$ = 0.267 mg/g, while the PSO model also produced a strong correlation ($R^2$ = 0.9065) and a calculated equilibrium capacity ($q_{e,\,cal}$ = 0.315 mg/g) close to the experimental value. This indicates that phosphorus adsorption onto zeolite can be adequately described by either model, although PFO shows a slightly better fit.

Overall, these findings indicate that ammonium and nitrate adsorption on zeolite follow the PSO model more closely, implying a chemisorption mechanism with stronger interactions between the adsorbate and the adsorbent. The finding is consistent with earlier studies [24], [31], [40], which reported that ammonium and nitrate adsorption onto zeolite is better described by the PSO model than by the PFO model. In contrast, phosphorus adsorption conformed more closely to the pseudo-first-order model, indicating that physisorption processes may dominate its removal.

## 4. Conclusion

The ability of zeolite to remove ammonium, nitrate and phosphorus from real industrial wastewater was successfully demonstrated through batch adsorption experiments. The SEM analysis demonstrated significant changes in the surface morphology of zeolite before and after adsorption treatment. The findings showed that the

zeolite's initially porous and rough surface became smoother and less porous after adsorption, indicating successful attachment of nutrients onto the zeolite surface. These morphological changes confirm the effective adsorption of ammonium, nitrate and phosphorus during the treatment process. Next, the findings on optimisation and adsorption performance revealed that the removal efficiency was significantly influenced by several parameters, including the percentage of wastewater, zeolite dosage, pH, and contact time. Optimal conditions for nutrient removal were identified at 10% (v/v) wastewater with 1.2 g of zeolite, at pH 7 and a contact time of 120 minutes. Under these conditions, zeolite achieved high removal efficiencies of 32% for ammonium, 67% for nitrate, and 59% for phosphorus, confirming its potential as an effective adsorbent. The adsorption behaviour of nutrients on zeolite demonstrated distinct mechanisms. Ammonium adsorption was more consistent with the Freundlich model, suggesting heterogeneous surface interactions, while nitrate was best described by the Langmuir model, indicating monolayer adsorption on uniform active sites. Phosphorus showed poor conformity to both isotherm models, implying that additional processes beyond simple surface adsorption may be involved. Kinetic studies revealed that ammonium adsorption followed the pseudo-second-order model, indicating that chemisorption is the dominant mechanism. Nitrate exhibited a lower correlation but was still better fit by the pseudo-second-order model than by the pseudo-first-order model. In contrast, phosphorus adsorption conformed more closely to the pseudo-first-order model, indicating that physisorption processes may dominate its removal. Future research may focus on practical applications, such as fixed-bed column experiments or continuous-flow systems, to better simulate industrial operations. Studies on regeneration and reusability would also be useful to assess the long-term applicability of zeolite, while hybrid systems combining zeolite with other natural or biological adsorbents could further improve nutrient removal efficiency.

## Acknowledgement

This work received financial support from Universiti Malaysia Perlis (UniMAP) through the Collaborative Research Grant (CRG) in collaboration with IIUM, UMPSA, and Taf Agriculture Trading & Services (Grant No: 9023-00032).

## Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## Author Contribution

*The authors confirm contribution to the paper as follows:* ***Study conception and design:*** *Ain Nihla Kamarudzaman, Norwahidatul Azura Zainon Najib, Dzun Noraini Jimat, Yunita Pane;* ***Data collection:*** *Julia Anne Anak Lidam, Salwa Mohd Zaini Makhtar, Mahyun Ab Wahab;* ***Analysis and interpretation of results:*** *Ain Nihla Kamarudzaman, Julia Anne Anak Lidam, Norwahidatul Azura Zainon Najib;* ***Draft manuscript preparation:*** *Ain Nihla Kamarudzaman, Nor Amirah Abu Seman. All authors reviewed the results and approved the final version of the manuscript.*

## References

[1] Kumar, A., Thakur, A., & Panesar, P.S. (2023). A review on the industrial wastewater with the efficient treatment techniques. Chemical Papers, 77, 4131-4163. https://doi.org/10.1007/s11696-023-02779-3

[2] Rodríguez-Vidal, F. J., Ortega-Azabache, B., González-Martínez, Á., & Bellido-Fernández, A. (2022). Comprehensive characterization of industrial wastewaters using EEM fluorescence, FT-IR and 1H NMR techniques. Science of the Total Environment, 805, 150417. https://doi.org/10.1016/j.scitotenv.2021.150417

[3] Razman, K. K., Hanafiah, M. M., Ramli, A. N., & Harun, S. N. (2023). Industrial wastewater treatment methods employed in Southeast Asian countries. IOP Conference Series: Earth and Environmental Science, 1167, 012020. https://doi.org/10.1088/1755-1315/1167/1/012020

[4] Amin, M., Tahir, F., Ashfaq, H., Akbar, I., Razzaque, N., Haider, M. N., Xu, J., Zhu, H., Wang, N., & Shahid, A. (2022). Decontamination of industrial wastewater using microalgae integrated with biotransformation of the biomass to green products. Energy Nexus, 6, 100089. https://doi.org/10.1016/j.nexus.2022.100089

[5] Fetahi, T. (2019). Eutrophication of Ethiopian water bodies: a serious threat to water quality, biodiversity and public health. African Journal of Aquatic Science, 44, 303-312. https://doi.org/10.2989/16085914.2019. 1663722

[6] Tan, Y. H., Chai, M. K., Na, J. Y., & Wong, L. S. (2023). Microalgal growth and nutrient removal efficiency in non-sterilised primary domestic wastewater. Sustainability (Switzerland), 15, 1–13. https://doi.org/10.3390/ su15086601

[7] Grout, L., Chambers, T., Hales, S., Prickett, M., Baker, M. G., & Wilson, N. (2023). The potential human health hazard of nitrates in drinking water: A media discourse analysis in a high-income country. Environmental Health: A Global Access Science Source, 22, 1–11. https://doi.org/10.1186/s12940-023-00960-5

[8] Sukmana, H., Bellahsen, N., Pantoja, F., & Hodur, C. (2021). Adsorption and coagulation in wastewater treatment – Review. Progress in Agricultural Engineering Sciences, 17, 49–68. https://doi.org/10.1556/446. 2021.00029

[9] Hasan, M. N., Altaf, M. M., Khan, N. A., Khan, A. H., Khan, A. A., Ahmed, S., … Islam, S. (2021). Recent technologies for nutrient removal and recovery from wastewaters: A review. Chemosphere, 277, 130328. https://doi.org/ 10.1016/j.chemosphere.2021.130328

[10] Ejike, D. U., Zamathula, Q. S. N., Michael, A. D., Michael, T. M., & Alexander, O. (2024). Review of emerging technologies for nutrient removal in wastewater treatment. World Journal of Advanced Research and Reviews, 21, 1737–1749. https://doi.org/10.30574/wjarr.2024.21.2.0520

[11] Kaczorowska, M. A., & Bożejewicz, D. (2024). The application of chitosan-based adsorbents for the removal of hazardous pollutants from aqueous solutions - A review. Sustainability, 16, 2615. https://doi.org/ 10.3390/su16072615

[12] Pająk, M. (2023). Alum sludge as an adsorbent for inorganic and organic pollutants removal from aqueous solutions: A review. International Journal of Environmental Science and Technology, 20, 10953–10972. https://doi.org/10.1007/s13762-023-04854-4

[13] Mohsin, M., Kaipiainen, E., Salam, M. M. A., Evstishenkov, N., Nawrot, N., Villa, A., Wojciechowska, E., Kuittinen, S., & Pappinen, A. (2021). Biomass production and removal of nitrogen and phosphorus from processed municipal wastewater by Salix schwerinii: A field trial. Water, 13, 2298. https://doi.org/10.3390/ w13162298

[14] Guaya, D., Jiménez, R., Sarango, J., Valderrama, C., & Cortina, J. L. (2021). Iron-doped natural clays: low-cost inorganic adsorbents for phosphate recovering from simulated urban treated wastewater. Journal of Water Process Engineering, 43, 102274. http://dx.doi.org/10.1016/j.jwpe.2021.102274

[15] López-Rosales, L., López-García, P., Benyachou, M. A., Molina-Miras, A., Gallardo-Rodríguez, J.J., Cerón-García, M.C., Sánchez Mirón, A., & García-Camacho, F. (2022). Treatment of secondary urban wastewater with a low ammonium-tolerant marine microalga using zeolite-based adsorption. Bioresource Technology, 359, 127490. https://doi.org/10.1016/j.biortech.2022.127490

[16] Urminská, B., Derco, J., Zakhar, R., & Korpicsová, A. (2019). Use of zeolites for macronutrients removal from wastewater. Acta Chimica Slovaca, 12, 150–161. http://dx.doi.org/10.2478/acs-2019-0021

[17] Hor, K. Y., Chee, J. M. C., Chong, M. N., Jin, B., Saint, C., Poh, P. E., & Aryal, R. (2016). Evaluation of physicochemical methods in enhancing the adsorption performance of natural zeolite as low-cost adsorbent of methylene blue dye from wastewater. Journal of Cleaner Production, 118, 197-209. https://doi.org/10.1016/j.jclepro.2016.01.056

[18] Bulacio Fischer, P. T., Di Trapani, D., Laudicina, V. A., Muscarella, S. M., & Mannina, G. (2025). Nutrient recovery from zeolite and biochar columns: The case study of Marineo (Italy) wastewater treatment plant. Water, 17, 848. https://doi.org/10.3390/w17060848

[19] Langmuir, I. (1916). The adsorption of gases on plane surfaces of glass, mica and platinum. Journal of the American Chemical Society, 40, 1361–1403. https://doi.org/10.1021/ja02242a004

[20] Freundlich, H. M. F. (1906). Over the adsorption in solution. The Journal of Physical Chemistry, 57, 385–471.

[21] Lagergren, S. (1898). About the theory of so-called adsorption of soluble substances. Kungliga Svenska Vetenskapsakademiens Handlingar, 24, 1–39. https://sid.ir/paper/563615/en

[22] Ho, Y. S., & Gordon, M. (1998). The kinetics of sorption of basic dyes from aqueous solution by sphagnum moss peat. Canadian Journal of Chemical Engineering, 76, 822–827. https://doi.org/10.1002/cjce. 5450760419

[23] Zhao, R., Wang, G., Chen, H., Zhou, S., Sun, X., Wang, D., … Li, Z. (2023). Simultaneous removal of nitrogen and phosphorus from urban sewage by synthetic zeolites adsorption: Performance, characterization, and mechanism. Desalination and Water Treatment, 303, 59–69. https://doi.org/10.5004/dwt.2023.29747

[24] Nguyen, T. D., Nguyen, T. M. P., Van, H. T., Nguyen, V. Q., Nguyen, L. H., Nguyen, T. D., … Thang, P. Q. (2022). Adsorption removal of ammonium from aqueous solution using Mg/Al layered double hydroxides-zeolite composite. Environmental Technology and Innovation, 25, 102244. https://doi.org/10.1016/j.eti.2021. 102244

[25] Safie, N. N., & Zahrim, A. Y. (2021). Recovery of nutrients from sewage using zeolite-chitosan-biochar adsorbent: current practices and perspectives. Journal of Water Process Engineering, 40, 101845. https://doi.org/0.1016/j.jwpe.2020.101845

[26] Kotoulas, A., Agathou, D., Triantaphyllidou, I. E., Tatoulis, T. I., Akratos, C. S., Tekerlekopoulou, A. G., & Vayenas, D. V. (2019). Zeolite as a potential medium for ammonium recovery and second cheese whey treatment. Water, 11, 136. https://doi.org/10.3390/w11010136

[27] Abdulredha, M., Kadhim, N. R., Hussein, A. H., Almutairi, M., Alkhaddar, R., Yeboah, D., & Hashim, K. (2021). Zeolite as a natural adsorbent for nitrogenous compounds being removed from water. *IOP Conference Series:* Materials Science and Engineering, 1067, 012082. https://doi.org/10.1088/1757-899x/1067/1/012082

[28] Nur Afikah (2024). Nutrients removal from industrial wastewater using zeolite-adsorption and chlorella vulgaris phycoremediation. Dissertation, Universiti Malaysia Perlis.

[29] Ram, A. K., Nilesh, M.P., Pradnya, G.K., & Sopan, I. (2023). Fly ash derived nano-zeolite for removal of nitrate, sulphate and phosphate from industrial effluent. Research Journal of Chemistry and Environment, 27, 109–119. http://dx.doi.org/10.25303/2705rjce1090119

[30] Shavandi, M. A., Haddadian, Z., Ismail, M. H. S., Abdullah, N., Abidin, Z. Z. (2012). Removal of Fe(III), Mn(II) and Zn(II) from palm oil mill effluent (POME) by natural zeolite. Journal of the Taiwan Institute of Chemical Engineers, 43, 750–759. https://doi.org/10.1016/j.jtice.2012.02.014

[31] Nasir, N., Daud, Z., Kadir, A. A., Aziz, A., Latiff, A., Ahmad, B., … Halim, A. A. (2019). Removal of ammonia nitrogen from rubber industry wastewater using zeolite as adsorbent. Malaysian Journal of Fundamental and Applied Sciences, 15, 862-866. https://doi.org/10.11113/mjfas.v15n6.1449

[32] De Magalhães, L. F., Da Silva, G. R., & Peres, A. E. C. (2022). Zeolite application in wastewater treatment. Adsorption Science and Technology, 2022, 4544104. https://doi.org/10.1155/2022/4544104

[33] Ruiz-Cosgaya, L., Izquierdo, W. A., Martínez-Guijarro, R., Serralta, J., & Barat, R. (2024). Ion exchange columns. A promising technology for nitrogen and phosphorus recovery in the main line of a wastewater treatment plant. Journal of Environmental Management, 370, 122719. https://doi.org/10.1016/j.jenvman.2024. 122719

[34] Mohammed, R. R. (2013). Decolorisation of biologically treated palm oil mill effluent (pome) using adsorption technique. International Refereed Journal of Engineering and Science, 2, 1–11.

[35] Wu, D., Zhang, B., Li, C., Zhang, Z., & Kong, H. (2006). Simultaneous removal of ammonium and phosphate by zeolite synthesized from fly ash as influenced by salt treatment. Journal of Colloid and Interface Science, 304, 300–306. https://doi.org/10.1016/j.jcis.2006.09.011

[36] Abdelhay, A., Al Bsoul, A., Al-Othman, A., Al-Ananzeh, N. M., Jum'h, I., & Al-Taani, A. A. (2018). Kinetic and thermodynamic study of phosphate removal from water by adsorption onto (Arundo donax) reeds. Adsorption Science and Technology, 36, 46–61. https://doi.org/10.1177/0263617416684347

[37] Widiastuti, N., Wu, H., Ang, H. M., & Zhang, D. (2011). Removal of ammonium from greywater using natural zeolite. Desalination, 277, 15-23. https://doi.org/10.1016/j.desal.2011.03.030

[38] Oyekanmi, A. A., Latiff, A. A. A., Daud, Z., Mohamed, R. M. S. R., Aziz, N. A. A., Ismail, N., … Hossain, K. (2019). Adsorption of pollutants from palm oil mill effluent using natural adsorbents: Optimization and isotherm studies. Desalination and Water Treatment, 169, 181–190. https://doi.org/10.5004/dwt.2019.24689

[39] Wang, S., & Peng, Y. (2010). Natural zeolites as effective adsorbents in water and wastewater treatment. Chemical Engineering Journal, 156, 11–24. https://doi.org/10.1016/j.cej.2009.10.029

[40] Yang, H., He, H., & Yan, Y. (2021). Study on the effect of modified zeolite on treating nitrate in water and its influencing factors. E3S Web of Conferences, 257, 03058. https://doi.org/10.1051/e3sconf/202125703058