



Research Article

Impacts of Temperature on Ammonium Migration: Simulation from An Unsanitary Landfill in Vietnam

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Abstract

Understanding the effects of temperature variations on pollutant dynamics is crucial for enhancing the accuracy of simulations of contaminant transport under climate change scenarios and groundwater protection. This study examines how temperature influences the migration of ammonium (NH_4^+) through silty sandy soils at an unsanitary landfill. Laboratory tests were used to measure the adsorption, diffusion, and permeability coefficients of these soils at four temperatures: 10 °C, 20 °C, 40 °C, and 50 °C. The results indicated that the apparent distribution coefficient (K_{ad}) peaked at 20 °C but decreased at lower (10 °C) and higher (40–50 °C) temperatures. Diffusion analysis revealed that the diffusion coefficient increased from $5.0 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ at 10 °C to $2.0 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ at 50 °C, indicating that the ammonium diffusivity increases rapidly with temperature. Moreover, the hydraulic conductivity of the sand increased with both temperature and ammonium concentration, with the permeability increasing slightly from $1.46 \times 10^{-6} \text{ m s}^{-1}$ at 10 °C to $1.63 \times 10^{-6} \text{ m s}^{-1}$ at 50 °C. The simulations confirmed that the relationship between temperature and break-through behavior is nonmonotonic, reflecting coupled physicochemical transport and the competing influences of advection, diffusion, and adsorption processes. These findings highlight the urgent need for technical and management solutions to minimize environmental risks.

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Introduction

Landfills not only serve as waste containment facilities but also pose numerous environmental and health risks, especially from unsanitary landfills (Siddiqua et al., 2022). These unsanitary landfills often lack proper waste treatment systems, leachate containment, and liners, which results in waste decomposing openly and potentially polluting soil, groundwater, and surface water (Iravanian and Ravari, 2020; United Nations Environment Programme, 2013). According to Trang and Nakakubo (2025), Vietnam has approximately 4,421 landfill sites, with only 443 classified as sanitary landfills, accounting for approximately 10%. These

findings indicate that nearly 90% of the country's landfills are unsanitary, creating a major challenge for waste management and environmental health.

Moreover, climate change, especially rising temperatures, exacerbates these issues as ongoing unsanitary landfills continue to harm the environment (Brand and Spencer, 2024; Qui et al., 2022). The IPCC Sixth Assessment Report (AR6) predicts a global temperature increase of 1.5–2.0 °C by mid-century, introducing new risks to landfill stability and safety (Intergovernmental Panel on Climate Change, 2023). Climate change influences both minimum and maximum temperatures by increasing both, which narrows the gap between

daily high and low temperatures (United States Environmental Protection Agency, 2005). Otherwise, landfill environments often experience elevated temperatures because of the biodegradation of organic waste and associated microbial activity. Previous studies have reported that temperatures within landfill waste bodies commonly range between 40 and 60 °C, depending on waste composition, moisture content, and landfill age (Hanson et al., 2010; Koerner and Koerner, 2006; Townsend et al., 2015; Yeşiller et al., 2005). These fluctuations in temperature in waste containers could alter the properties of soil materials and geotechnical barriers and affect the processes of pollutant transport through soils or barrier materials (Cai et al., 2004; Gharabaghi ; Hoai et al., 2023a; 2023b; Qui et al., 2022; Rowe et al., 2004; Rowe and Powrie, 2005; Rowe and Arnepalli, 2008). Consequently, this greatly accelerates the movement of contaminants from wastewater into the subgrade soils and ground-water.

The vertical transport of contaminants within subsurface systems is governed by various mechanisms, including advection, diffusion, and adsorption (Rowe et al., 2004). Rowe and Arnepalli (2008) modeled the migration of dichloromethane (DCM) through a composite liner to groundwater under landfill temperatures of 10 °C–50 °C. Gharabaghi et al. (2015) examined how temperature (5 °C and 20 °C) affects the transport of Br and *E. coli* through soil columns. The results indicate that cold temperatures (5 °C) reduce the hydraulic conductivity and flow rates of these contaminants. Qui et al. (2022) proposed an analytical solution for pollutant transport, specifically through adsorption and diffusion through lining systems such as geomembranes (GMBs) under nonisothermal conditions.

Ammonium (NH_4^+) is widely recognized as one of the most problematic contaminants generated in leachates of municipal solid waste landfills during waste decomposition (Kjeldsen et al., 2002; Koda et al., 2015). NH_4^+ released into the environment can cause eutrophication, reduce dissolved oxygen, and harm ecosystems. Soil contaminated with ammonium can seep deep and pollute groundwater sources (Koda et al., 2015). In addition to negatively affecting groundwater quality, elevated concentrations of NH_4^+ can be transformed through nitrification into nitrite and nitrate, which are compounds that cause adverse effects on human health outcomes. Given these risks, understanding the migration behavior of NH_4^+ in soil and groundwater is essential for effective contamination assessment and remediation planning. The impact of temperature on NH_4^+ migration through bentonite and clayey soils has been studied by Hoai et al. (2023a; b) The authors investigated how temperatures of 20 °C, 35 °C, and 50 °C affect the adsorption, diffusion, and hydraulic conductivity of bentonite–clay mixtures.

Although the effects of temperature on NH_4^+ behavior have been studied in clayey materials, this work fills a critical gap by focusing on silty sand across a broad thermal spectrum from 10 °C to 50 °C. The selection of the 10–50 °C range aims to provide a comprehensive thermal profile, spanning from low-temperature subsurface environments to the elevated temperatures typically observed in landfills. In particular, the present study integrates experimental results into a predictive simulation model, whereas previous studies have primarily provided empirical data. Furthermore, it is critical to note that temperature changes do not merely exert physical transport effects. Thermal variations also profoundly influence chemical effects, including adsorption–desorption dynamics, ion exchange, and $\text{NH}_4^+/\text{NH}_3^-$ speciation. Therefore, this study treats the thermal migration of NH_4^+ in sandy soil as a coupled physical–chemical transport mechanism, which is vital for long-term environmental risk assessment.

Materials and methods

1) Study area

The Quang Binh (QB) unsanitary landfill is located in Hung Yen Province, within the Red River Delta region of northern Vietnam (Figure 1). It has been in operation since 2019, with an area of 4,000 m². The landfill is approximately within a radius of 1 km and includes houses, fields, rivers, and canals. The amount of waste dumped every day includes leftover food, plastic bags, leaves, rubber, fabrics, and some types of hazardous waste, such as electronic devices, light bulbs, batteries, etc. The landfill is currently overloaded, which poses potential risks of contaminant migration to soil and groundwater. According to Huyen et al. (2024), the NH_4^+ concentration in groundwater at the landfill site exceeded QCVN 09-MT:2023/BTNMT (Ministry of Natural Resources and Environment, 2023).

In reference to Tran Nghi et al. (2017), the stratigraphic column of the landfill site is composed of five distinct lithological layers and belongs to the Thai Binh Formation. The uppermost layer consists of silty sand, extending from the surface to a depth of 13 meters. The lowermost identified layer is gravelly sand, extending from 40 m to the bottom of the column at 54 m (Figure 1).

The synthesis of monitoring hydrometeorological data between 2006 and 2023 reveals an upward trend in monthly mean temperatures. This represents an average increase of 0.6 °C compared to the baseline period of 1986–2005 (Ministry of Natural Resources and Environment, 2025). In addition, the region is becoming increasingly vulnerable to climate change, with evidence of abnormal maximum and minimum temperatures in recent years (Figure 2). A comparison with the previous two years reveals a slight increase in maximum temperatures in most months, particularly in spring and summer, indicating a clear warming trend.

Notably, in April, the maximum temperature reached 39.0 °C, while the lowest minimum temperature was 8.4 °C in January 2024. The difference between the maximum and minimum temperatures in summer (11.8–13.8 in June) is smaller than that in winter (15.3–20.3 in December), reflecting greater temperature stability during the hot season. The temperature data reveal that hot weather conditions (35 °C) tend to start earlier in 2024 than in the previous two years. Specifically, the maximum temperature exceeded 35 °C as early as April 2024 (39.0 °C), whereas this threshold was not reached until May 2023 and June 2022. In April 2022 and 2023, the temperature still reaches 31.5 °C and 31.7 °C, respectively (Ministry of Natural Resources and Environment, 2025). This change reflects an abnormal climate, with the risk of prolonging the period affected by heat.

2) Field survey and sampling methods

Undisturbed soil samples from the Quang Binh landfill (QB soils) were collected at a depth of 1 m within the site using a column sampling method (Figure 3). During sampling, the soil temperature at the site was recorded at 25.8 °C. This method ensured the preservation of the natural soil structure; thus, laboratory experiments were performed to determine the charac-

teristic parameters of the ammonium ion (NH_4^+) migration process in the soil environment. The physical properties of the QB soils are summarized in Table 1. The soil has a water content of 27.74%, a specific gravity of 2.67, a dry density of 1.898 g cm⁻³, and a porosity of 0.29. The QB soil, classified as silty sand, consists of moderately fine particles smaller than 0.075 mm (15,3%) and has 2.91–4.0% organic matter.

3) Experiments for determining NH_4^+ migration parameters

Three hydraulic transport parameters of QB soils are examined, including the adsorption and diffusion coefficients and hydraulic conductivity. Three experiments were performed under different temperature conditions (10 °C, 20 °C, 40 °C, and 50 °C). Before the experiments were performed, a 1000 mg L⁻¹ NH_4Cl stock solution was prepared. This stock solution was then diluted to obtain working solutions with the required concentrations for each experiment. Notably, the pH of the ammonium solution in these experiments was measured and remained within the range of 5.54 to 7.05, indicating near-neutral conditions. Within this pH range, ammonium predominantly exists as NH_4^+ , which is unlikely to have significantly influenced the experimental results.



Figure 1 Location map and stratigraphic column of the Quang Binh unsanitary landfill in northern Vietnam.

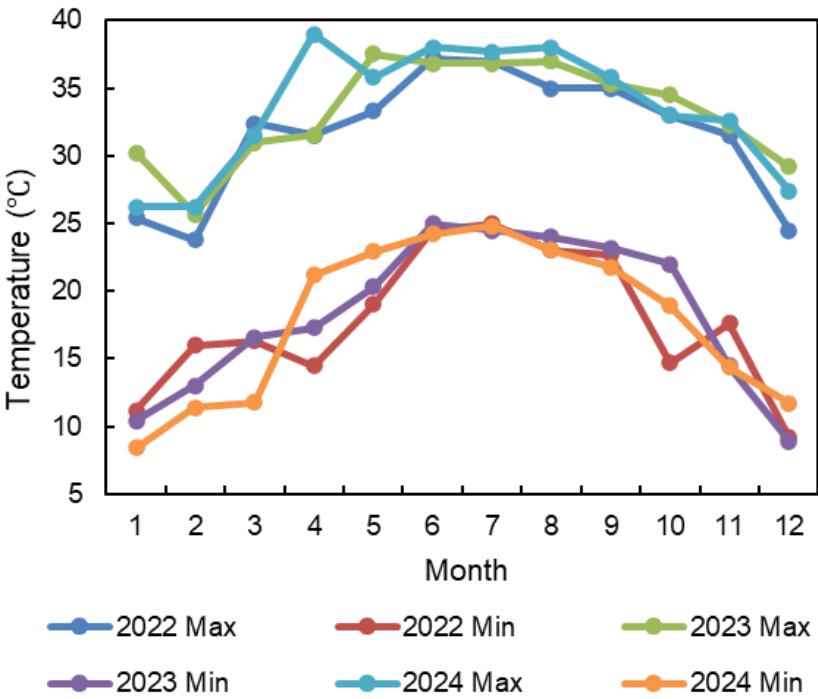


Figure 2 Monthly maximum and minimum temperatures (2022–2024).



Figure 3 Columnar sampling method.

Table 1 Physical properties of the QB soils

Property	Unit	Value
Percentage of particle size in mm		
0–0.05	(%)	8
0.05–0.075		7.3
0.075–0.15		43.1
0.15–0.3		38.9
>0.3		4.7
Water content	%	27.74
Specific gravity	cm ³ g ^{−1}	2.67
Dry density	g cm ^{−3}	1.898
Porosity	-	0.29
Soil organic matter (SOM)	%	2.91–4.0
Coefficient of permeability	cm s ^{−1}	1.87x10 ^{−4}
Classification (USCS)		Silty sand

Adsorption experiment: Adsorption experiments were performed at four temperatures (10 °C, 20 °C, 40 °C, and 50 °C) to investigate the effect of temperature on the ammonium adsorption capacity of QB soils (Figure 4a). For each test, 1 g of soil was placed in a 100 mL glass cup, and 100 mL of NH_4Cl solution was added to achieve a solid-to-liquid ratio of 10 g L^{-1} , with NH_4Cl concentrations of 10, 20, 50, 75, 100, 150, and 200 mg L^{-1} . Notably, the ammonium concentration in wastewater from the QB landfill was approximately 50 mg L^{-1} because of the dilution of the leachate by rainfall under open dumping conditions (Huyen et al., 2024). The maximum concentration of 200 mg L^{-1} , approximately four times the NH_4^+ concentration in the open-dumpsite leachate, was selected to extend the isotherm sufficiently

into the saturation region for reliable estimation of the maximum adsorption capacity and equilibrium parameters while remaining within a range of practical environmental relevance. Moreover, samples of ammonium solution C_0 without soil were prepared to control the initial concentration. The mixtures were stirred for 2.5 h to reach equilibrium, after which the suspensions were filtered through 0.45 μm filter paper, and the filtrates were analyzed to determine the residual ammonium concentration. These adsorption experiments were conducted in duplicate, and the results are presented as the mean $\pm$ standard deviation. Error bars have been added to the plots, and the R^2 values for each fitted model are also reported.

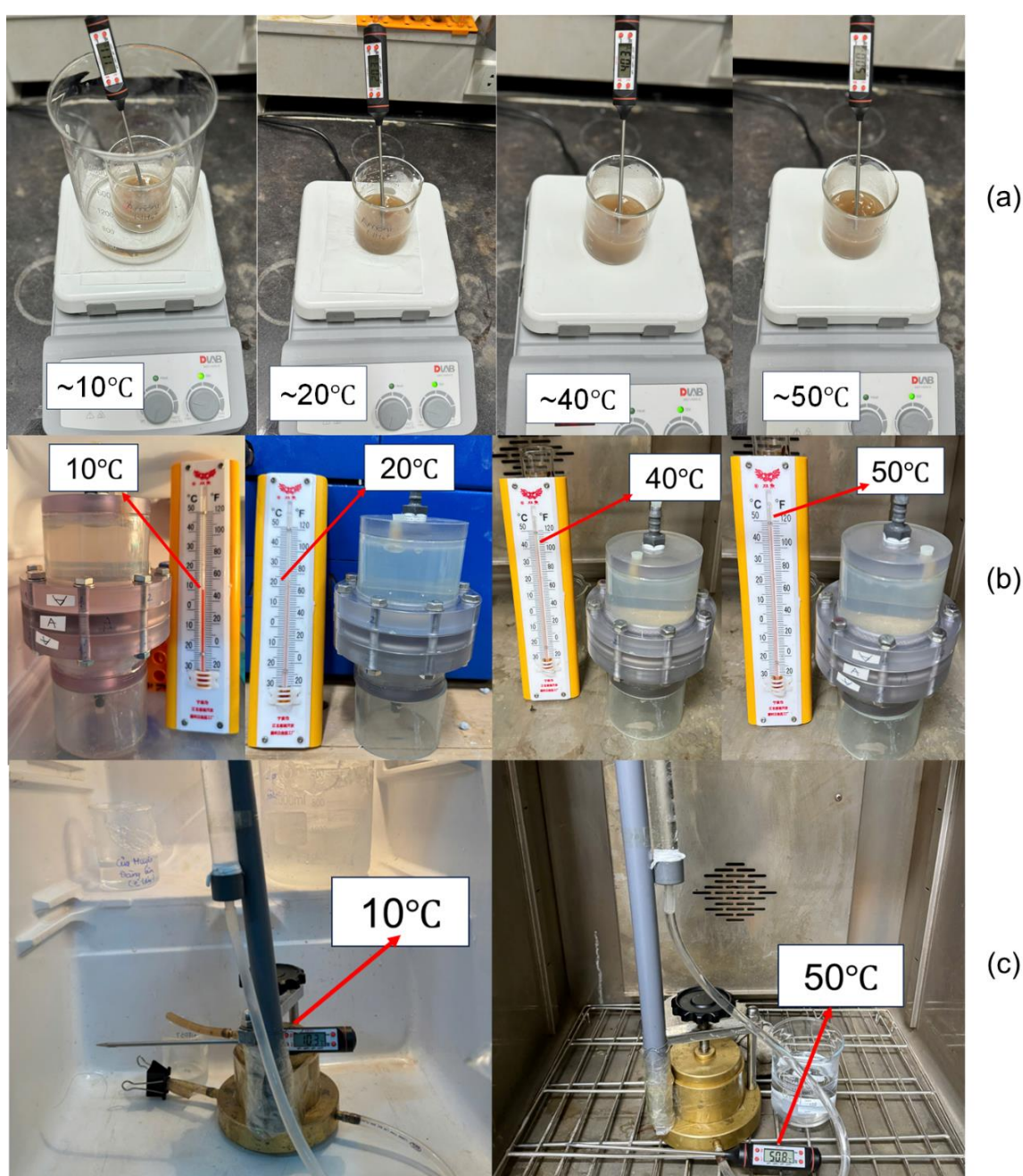


Figure 4 Adsorption (a), diffusion (b), and hydraulic conductivity (c) experiments at different temperatures (10, 20, 40, and 50 °C).

The adsorption behavior of NH_4^+ was evaluated using a linear isotherm model to determine the distribution coefficient (K_d). Within the investigated concentration range (10–200 mg L^{-1}), the relationship between the adsorbed concentration and aqueous concentration also exhibited an approximately linear trend, with no clear indication of adsorption saturation. Within this narrow concentration range, the various complex retention mechanisms (such as ion exchange and surface interactions) do not reach saturation. Consequently, the actual nonlinear adsorption curve behaves like a straight line, allowing it to be treated mathematically. To reflect this reality, this parameter is defined as the apparent linear distribution coefficient (K_{ad}), which serves as a practical and reliable input for transport simulations under these specific experimental conditions. Additionally, this approach was adopted because the primary objective of this study is to obtain K_{ad} values for contaminant transport modeling in porous media rather than to characterize the adsorption capacity of a specific adsorbent material.

Diffusion experiment: This test was conducted as described by Hoai et al. (2023b) (Figure 4b). The diffusion experiments were conducted in a temperature-controlled incubator. The incubator temperature was maintained at the target values (e.g., 10, 20, 40, and 50 °C), with a stability of approximately ± 0.5 °C. The temperature was monitored using a calibrated digital thermometer to ensure consistent experimental conditions throughout the diffusion tests. A 90 mm high and 50 mm wide cell made of vinyl chloride was used. A 15 mm thick layer of QB soil was placed between the two chambers. This thickness was selected to ensure a measurable concentration gradient within a reasonable experimental duration while maintaining one-dimensional diffusion conditions. Notably, the experimental setup was designed to investigate the relative effect of temperature on diffusion behavior rather than to replicate field-scale concentration gradients. A sample thickness of 15 mm was selected to ensure measurable diffusive transport within a reasonable experimental duration while maintaining a representative soil structure. The upper chamber contained 50 mg L^{-1} ammonium solution, and the lower tank was filled with distilled water. An initial ammonium concentration of 50 mg L^{-1} was selected to represent a moderate level relevant to diluted landfill leachate, as observed in QB landfill leachate (Huyen et al., 2024), and to enable stable analytical measurements. The test lasted 14 days, with approximately 1.0 mL of sample taken daily from both the upper and lower chambers, after which DI water was added to both chambers with the same volume. The ammonium concentration of these samples was then analyzed. Each diffusion experiment was conducted in duplicate to ensure reproducibility. To ensure the mathematical validity of this framework in a porous

medium, several key experimental assumptions were strictly controlled and satisfied in the setup: the system operated under one-dimensional transport, fully saturated soil conditions, zero advective hydraulic gradient, homogeneous soil packing, and well-mixed reservoirs. Furthermore, the diffusion cells were completely airtight, resulting in negligible evaporation and NH_3 volatilization.

To clarify the physical transport parameters, a clear distinction must be made between molecular diffusion (D_0), effective diffusion (D_e), and mechanical dispersion (D_m). Molecular diffusion (D_0) is an intrinsic property driven solely by concentration gradients in free water; its magnitude increases with temperature because of reduced fluid viscosity, as described by the Stokes–Einstein relationship. When solutes migrate through a porous medium such as soil, this molecular movement is physically hindered by twisted pathways and narrow pore throats, yielding D_e , which is inherently lower than D_0 because of tortuosity and constrictivity factors. In contrast, mechanical dispersion D_m is a distinct, purely hydrodynamic process driven by pore-water velocity and flow regimes rather than by concentration gradients. Temperature only indirectly influences D_m by altering fluid viscosity and hydraulic conductivity. In this study, the parameters obtained from POLLUTE fitting using the analytical solution of Fick's second law represent the D_e under transient conditions (Rowe et al., 2004). Because the chemical sorption aspect was handled by K_{ad} , the D_e strictly isolates the physical constraints of the sand matrix (porosity and geometric tortuosity), which ensures a realistic boundary for subsurface risk assessment.

Hydraulic conductivity experiment: Falling head hydraulic conductivity tests were conducted at 10 °C, 20 °C, 40 °C, and 50 °C to determine the hydraulic conductivity of QB soils following ASTM D5084 (ASTM International, 2010) (Figure 4c). The soil samples were undisturbed soils placed in the cell to preserve the natural soil structure and in situ conditions. No artificial compaction was applied. The bulk density of the samples was maintained close to that under in situ conditions because of the use of undisturbed samples. Before the permeability tests were performed, the samples were fully saturated by gradually introducing deaired water from the bottom of the column to avoid air entrapment. The permeability measurements were conducted in duplicate, and the reported hydraulic conductivity values represent the average of duplicate measurements.

In the hydraulic conductivity experiment, evaporation of the ammonium solutions under high-temperature conditions was considered negligible. The collected data were subsequently used to calculate the hydraulic conductivity (K) as shown in Eq. 1.

$$K = (aL/At)\ln(h_0/h_1) \quad (\text{Eq. 1})$$

where K denotes the coefficient of hydraulic conductivity, a is the area of the burette (2.01 cm^2), L is the length of the soil column (4.0 cm), A is the area of the soil column (29.64 cm^2), h_0 is the initial height of water, h_1 is the initial height of water $h_0 - \Delta h$, and t is the time required to obtain a head drop of Δh .

4) Ammonium analysis

Ammonium analysis was conducted on samples for the adsorption and diffusion experiments. For the adsorption test, samples were analyzed immediately after the adsorption experiment was completed. For the diffusion test, samples were collected daily and analyzed for 14 days. These samples were filtered using $0.45 \mu\text{m}$ filter paper and diluted before analysis. Afterward, various reagents are added and mixed thoroughly. The mixture is immersed in warm water at approximately 40°C for 15 minutes. The analysis was conducted using a UV-VIS spectrophotometer, specifically a VIS Hatch Dr6000 model with a wavelength of 640 nm .

5) Simulation of NH_4^+ ions through QB soils

To determine the diffusion coefficient, the values were iteratively adjusted until the modeled ammonium concentrations matched the experimental diffusion tests at both the source and the receptor. The optimal fit was assessed through visual comparison as well as the sum of squared errors (SSE). The theoretical diffusion framework of Rowe et al. (2004) and the SSE

approach were described in detail by Hoai et al. (2023b). The simulation of ammonium migration was conducted using the POLLUTE v7 software. The input data are the three abovementioned migration parameters combined with the geology and stratigraphy characteristics of the study area.

Results and discussion

1) Adsorption properties of QB soils

1.1) Effects of time on ammonium adsorption

The equilibration time for ammonium adsorption of QB soils at 20°C needs to be determined for conducting the adsorption test under low and high temperatures (10 , 40 , and 50°C). The effect of time (24 hours) on the ammonium adsorption capacity of the QB soil is shown in Figure 5. The adsorption capacity increased rapidly from 3.26 ± 0.49 to $5.83 \pm 0.41 \text{ mg g}^{-1}$ within the first 60 minutes because of the presence of abundant active sites and a high concentration gradient. In the subsequent stage (60 – 150 min), the adsorption rate began to slow, with Q_e gradually increasing from $5.83 \pm 0.41 \text{ mg/g}$ to $7.12 \pm 0.01 \text{ mg g}^{-1}$. The increased rate of adsorption slowed because of the gradual occupation of active sites, which reduced the number of sites available for further adsorption. In the final stage, after 150 min, the adsorption capacity approached a quasiequilibrium value, fluctuating slightly between $7.12 \pm 0.01 \text{ mg g}^{-1}$ and $7.23 \pm 0.02 \text{ mg g}^{-1}$ until 960 and $1,440$ min, respectively. As a consequence, subsequent experiments with QB soils were conducted at higher temperatures, with test intervals of 150 min.

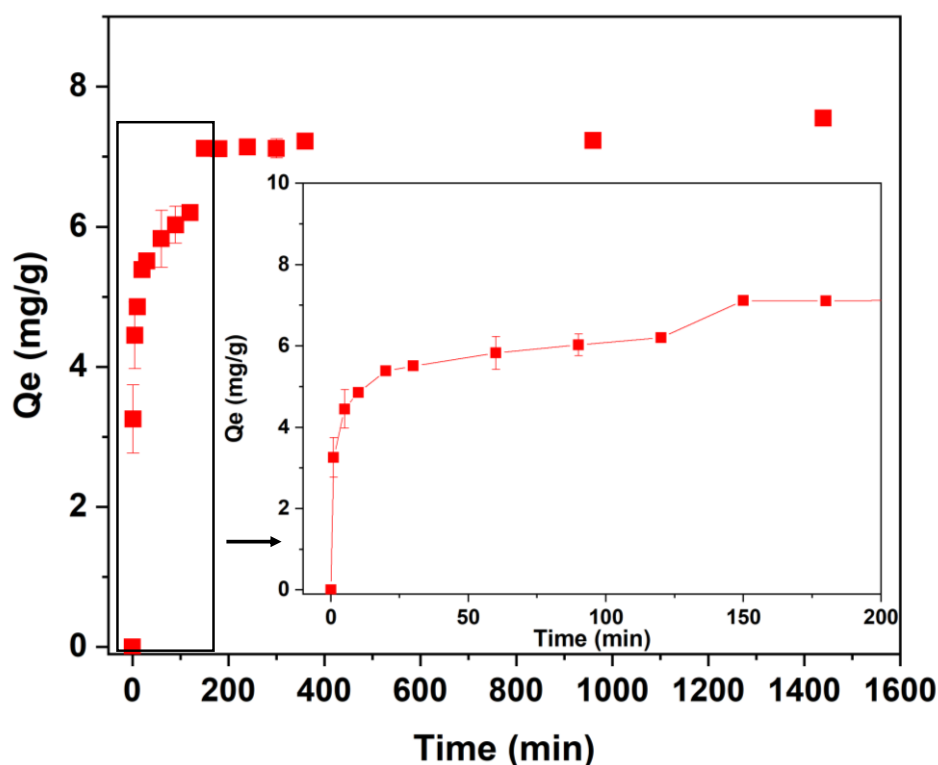


Figure 5 Effects of time on ammonium adsorption in QB soils.

1.2) Ammonium adsorption coefficient

The relationship between the amount of adsorbate at equilibrium (Q_e , mg g⁻¹) and the equilibrium concentration in solution (C_e , mg L⁻¹) at 10 °C, 20 °C, 40 °C, and 50 °C is shown in Figure 6. The results indicate that the linear adsorption model fits the experimental data well, with high correlation coefficients ($R^2 = 0.88$ – 0.99). The K_{ad} of the QB soils were relatively low, ranging from 0.075 to 0.11 mL g⁻¹. The tested soil contains approximately 15.3% fine particles (<0.075 mm), indicating a moderate fraction of silt and clay. Although detailed mineralogical analysis was not conducted, the presence of a moderately fine fraction together with the organic matter content (2.91–4.0%) suggests a limited to moderate cation exchange capacity. This, in turn, constrains the ammonium adsorption potential of the QB soil. Therefore, the observed K_{ad} value of 0.075–0.11 mL g⁻¹ can be considered moderate and is consistent with the expected behavior of sandy soils with relatively low reactive surface areas, as reported by Abdulgawad et al. (2009).

2) Diffusion properties of QB soils

Experimental data from the diffusive transport of NH_4^+ ions from the source and the receptor through QB soils at 4 temperatures within 14 days are shown as red and blue plots, respectively, in Figure 7. The results show that the diffusion of ammonium through the soil layers clearly depends on temperature. At 10 °C, the ammonium concentration in both layers gradually changed and reached equilibrium after approximately 13 days. When the temperature increases to 20 °C, equilibrium is reached faster, approximately 10 days. At 40 °C, the system requires only approximately 8 days to reach equilibrium, whereas at 50 °C, equilibrium is achieved in approximately 6 days. This trend indicates that increasing the temperature significantly enhances the diffusion rate of ammonium through the soil.

The D_e were deduced by iteratively solving for D_e using the software POLLUTE. The value of D_e was determined with the lowest SSE as a bold number in Table 2. The D_e value also increases with temperature, supporting the observed faster transport at higher temperatures. Specifically, the D_e values are nearly similar at 10 and 20 °C (5.0 – 5.5×10^{-10} m² s⁻¹) and at 40 and 50 °C (1.5 – 2.0×10^{-9} m² s⁻¹), respectively. The fitted effective diffusion coefficients ($D_e = 5.5 \times 10^{-10}$ m²/s) obtained from POLLUTE were compared with the standard molecular diffusion coefficient ($D_o = 1.98 \times 10^{-9}$ m² s⁻¹) of NH_4^+ in water at 25 °C (Hatfield et al., 1966).

The D_e / D_o ratio is equal to 0.28, which is lower than 1.0, indicating that NH_4^+ transport is substantially hindered by pore tortuosity, constrictivity, and adsorption effects within the porous medium. Additionally, the faster diffusion at elevated temperatures can be attributed to increased molecular motion, which reduces resistance to mass transfer within the soil matrix. Overall, these findings highlight the crucial role of temperature in controlling the migration of ammonium ions in soil environments.

3) Hydraulic conductivity of QB soils

The average permeability coefficient (K) of the QB soil was determined using permeant solutions, including deionized (DI) water and ammonium solutions of varying concentrations (50 mg L⁻¹, 200 mg L⁻¹, 500 mg L⁻¹, and 1,000 mg L⁻¹) (Figure 8). The 50 mg L⁻¹ condition corresponds to the typical NH_4^+ concentrations found in leachate from open dumpsites (Huyen et al., 2024), providing realistic estimates of hydraulic performance, while the higher concentrations (200–1,000 mg L⁻¹) simulate more concentrated leachate scenarios. The upper limit of 1000 mg L⁻¹ reflects the elevated NH_4^+ concentrations commonly reported in leachate from some Vietnamese landfills (Luu, 2020; Son et al., 2017). This concentration range allows a comprehensive assessment of the long-term hydraulic stability of soils under fluctuating leachate.

In DI water, the K value was approximately 1.99×10^{-6} m s⁻¹. When exposed to ammonium solutions, the permeability coefficients increased progressively with increasing ammonium concentration: 2.04×10^{-6} m s⁻¹ at 50 mg L⁻¹, 2.13×10^{-6} m s⁻¹ at 200 mg L⁻¹, 2.27×10^{-6} m s⁻¹ at 500 mg L⁻¹, and 2.37×10^{-6} m s⁻¹ at 1000 mg L⁻¹. This trend clearly indicates that the permeability of the soil is positively correlated with the ammonium concentration in the pore water. A similar pattern was observed by Harun et al. (2013), who reported that the permeability of sandy soil increased when it was exposed to landfill leachate containing high ammonium levels. Similarly, Jellali et al. (2010) reported that ammonium infiltration through sandy columns altered pore connectivity and facilitated faster water movement. These findings suggest that NH_4^+ ions can modify pore structure by reducing interparticle repulsion and enhancing flocculation, which increases the number of effective flow channels. Consequently, ammonium contamination can significantly influence the hydraulic behavior of sandy soils, potentially accelerating the migration of pollutants into groundwater.

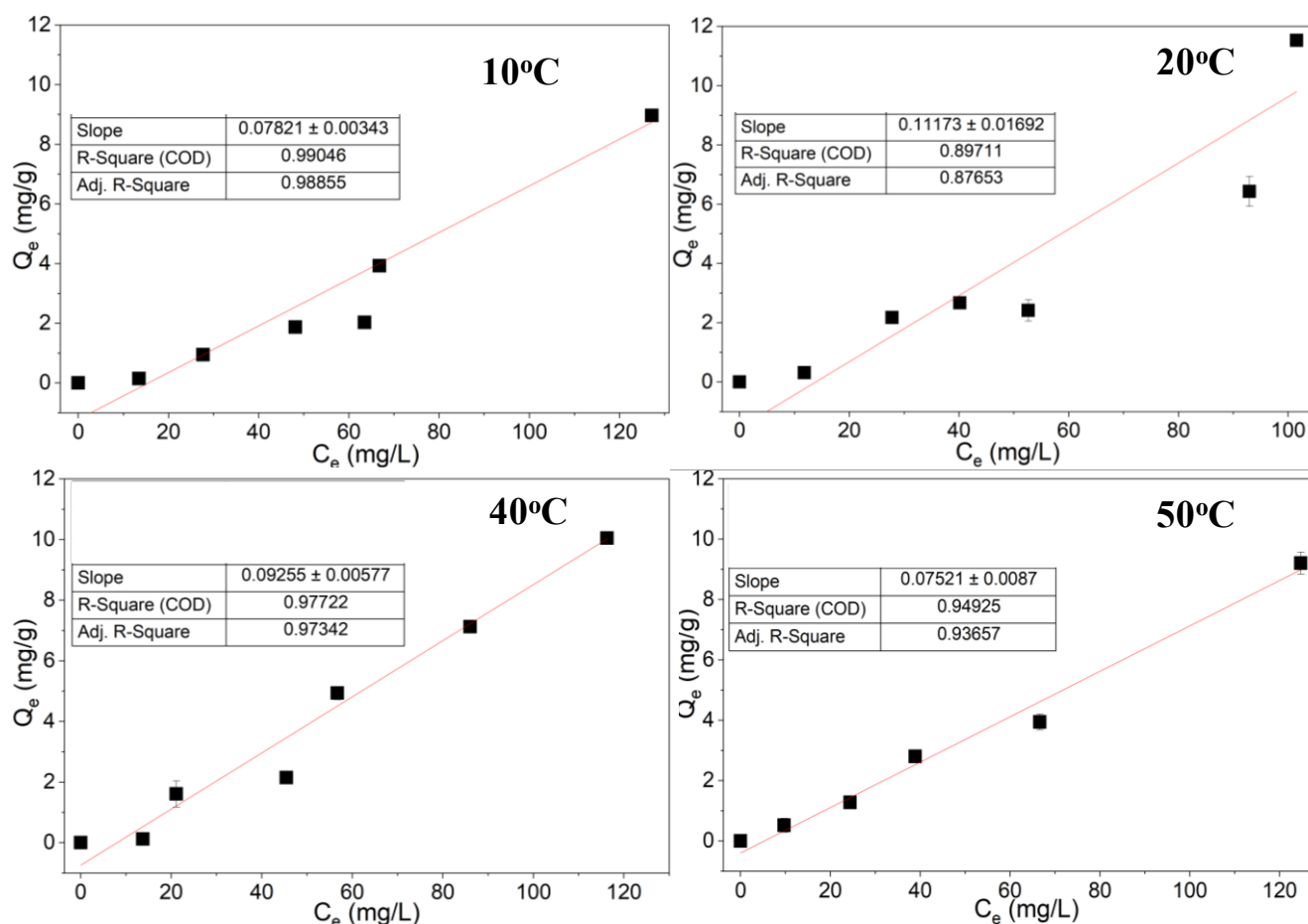


Figure 6 Ammonium adsorption of QB soils at different temperatures.

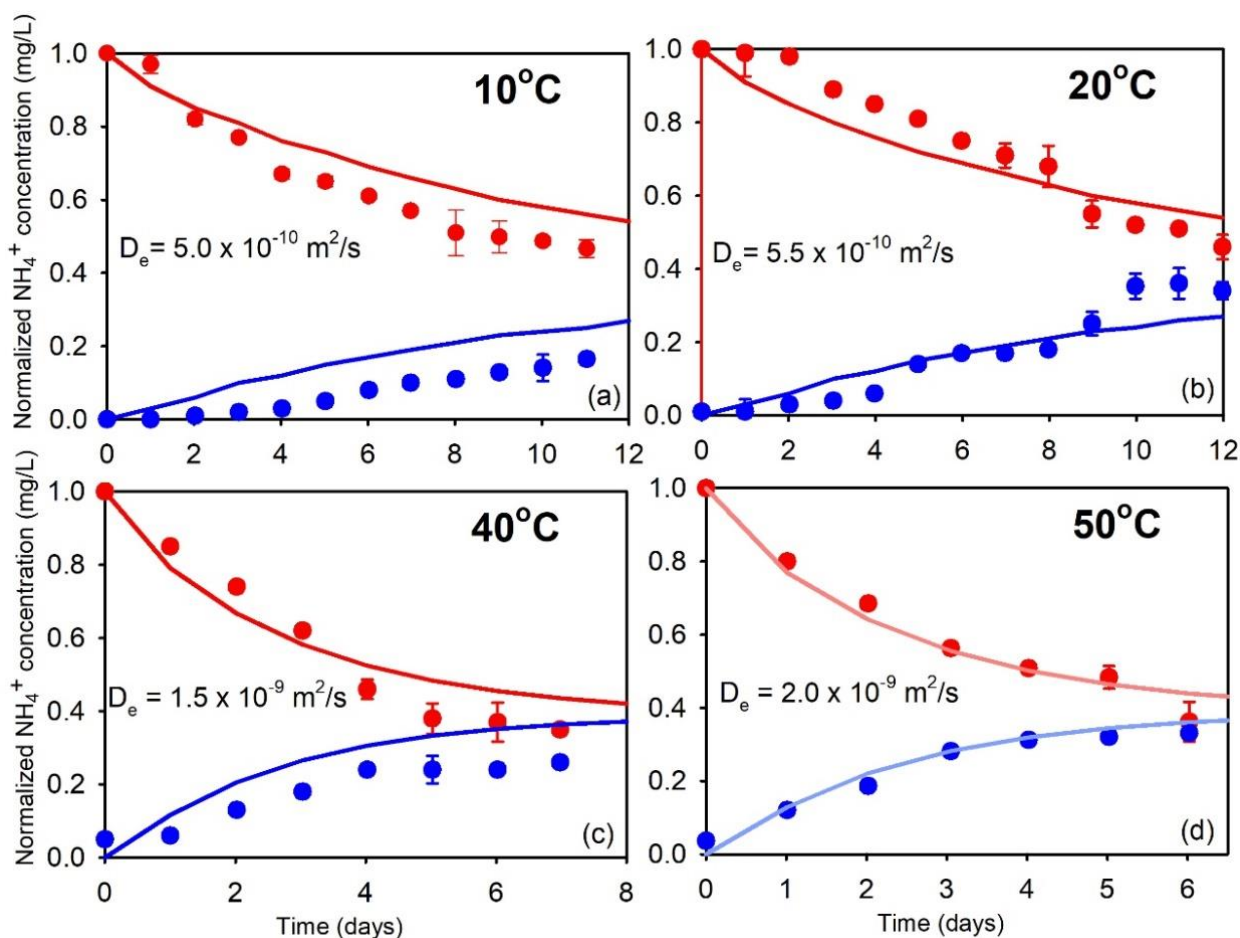


Figure 7 The diffusion of ammonium through QB soils at different temperatures.

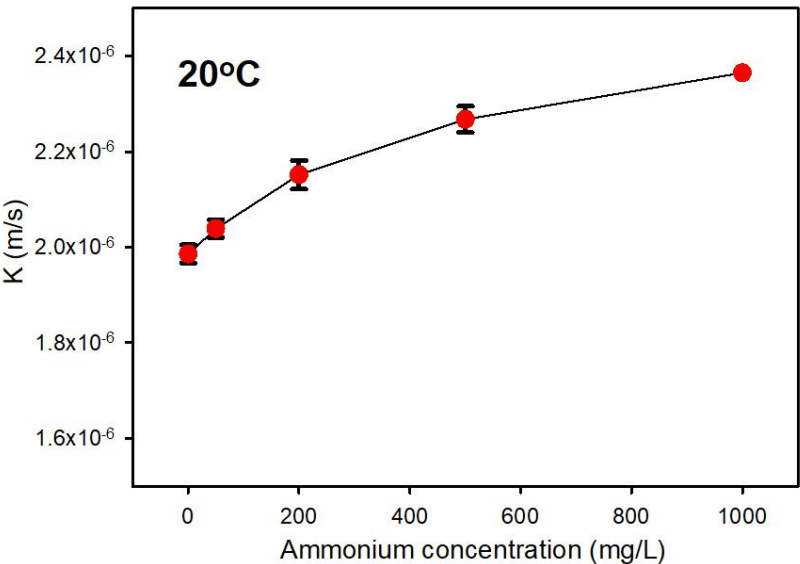


Figure 8 Permeability coefficient of QB soils with various concentrations of ammonium.

Table 2 SSE and D_e values of QB soil at different temperatures (T)

T (°C)	D_e	SSE	D_e	SSE	D_e	SSE	D_e	SSE
10	4×10^{-10}	0.58	5.0×10^{-10}	0.19	6×10^{-10}	0.71	-	-
20	5×10^{-10}	0.15	5.5×10^{-10}	0.11	6×10^{-10}	0.18	-	-
40	-	-	1.0×10^{-9}	0.13	1.5×10^{-9}	0.11	2.0×10^{-9}	0.15
50	-	-	1.0×10^{-9}	0.18	2.0×10^{-9}	0.03	3×10^{-9}	0.08

4) Effects of temperature on NH_4^+ transport parameters

4.1) Effects of temperature on the apparent distribution coefficient

The apparent distribution coefficient varies with temperature from 10 °C to 50 °C, as shown in Figure 9a. The apparent distribution coefficient K_{ad} does not show a consistent linear trend across this range. It initially increases from 10 °C to 20 °C, reaching a peak, and then gradually decreases as the temperature increases further to 40 °C and 50 °C. This finding indicates that the affinity of the adsorbent for the pollutant is optimal at approximately room temperature (approximately 20 °C) within the tested range. Both lower and higher temperatures tend to decrease the adsorption capacity. These results align with those of previous studies, such as those of Hoai et al. (2023b), Chen et al. (2018), and Hoai et al. (2025). Hoai et al. (2023b) studied the impact of temperature on ammonium transport through natural clayey soils in Hanoi and their mixture with bentonite. In their findings, the K_d value increased with temperature upto approximately 20–35 °C but then decreased at higher temperatures (up to 50 °C). Similar trends were reported by Chen et al. (2018), who investigated NH_4^+ removal using natural zeolites (mordenite, chabazite, and erionite). They reported that the adsorption efficiency peaked at approximately 76–82% at approximately 30 °C but decreased significantly at both lower (≤ 20 °C) and higher temperatures (≥ 40 °C).

In addition, Q_e increases with increasing C_e concentration at all temperatures, making the adsorption process more favorable at higher initial concentrations. The highest K_{ad} value was obtained at 20 °C (0.11 mL g^{-1}), indicating that the most efficient adsorption occurred at room temperature. As the temperature increased to 40 °C and 50 °C, K_{ad} decreased slightly, indicating a slight reduction in the QB soil adsorption capacity with increasing temperature. The observed decrease in K_{ad} at elevated temperatures suggests that the equilibrium shifts toward the formation of NH_3 as the temperature increases, which is uncharged and therefore less strongly adsorbed onto soil surfaces than NH_4^+ is (Huang et al., 2010). This results in a reduction in apparent adsorption capacity at higher temperatures.

In addition, the adsorption of NH_4^+ in soils occurs primarily through cation exchange processes. At higher temperatures, increased ionic mobility and potential competition from other cations (e.g., Na^+ , K^+ , and Ca^{2+}) may further reduce NH_4^+ retention (Davis et al., 2024; Yang and Yang, 2024). These combined effects may explain the observed decrease in K_{ad} at elevated temperatures.

4.2) Effects of temperature on the effective diffusion coefficient

The variation in the effective diffusion coefficient with respect to temperature is clearly illustrated in Figure 9b. It remains low and fairly constant at 10 °C and 20 °C but increases notably at 40 °C and 50 °C. This aligns with diffusion theory, which states that

higher temperatures increase molecular kinetic energy, resulting in faster diffusion. These results agree with those of prior research. For instance, Wang et al. (2022a) reported a nonlinear increase in water molecule diffusion in clay vermiculite between 275 K and 425 K (approximately 2 °C to 152 °C), indicating that increased thermal energy enhances molecular mobility. Similarly, Inselsbacher and Näsholm (2012) reported that the diffusive flux of plant-available nitrogen in soil increases with temperature. These studies support the current findings that temperature significantly influences the diffusion of ammonium in porous soils. In this study, the observed increase in D_e with temperature is driven primarily by the enhanced thermal kinetic energy of D_0 within the pore water, whereas the contribution of D_m remains negligible. Consequently, while temperature variations significantly modify the kinetic rate of transport, they do not alter the fundamental Fickian driving force governed by the concentration gradient.

4.3) Effects of temperature on hydraulic conductivity

The variations in the average permeability coefficient with respect to temperature are shown in Figure 9c. As the temperature increases from 10 °C to 50 °C, the permeability coefficient tends to increase consistently and slightly from $1.46 \times 10^{-6} \text{ m s}^{-1}$ to $1.63 \times 10^{-6} \text{ m s}^{-1}$. This trend was confirmed by He et al. (2024), who tested the permeability of sand from 13.2 °C to 49.2 °C under controlled laboratory conditions. The observed variation in hydraulic conductivity with temperature is relatively modest, which is consistent with the behavior of silty sand soils where permeability is primarily controlled by pore structure rather than temperature. The increase in hydraulic conductivity with temperature is attributed primarily to the reduction in fluid viscosity (Wang et al., 2022b) according to the following formula shown in Eq. 2.

$$K = kpg/\mu(T) \quad (\text{Eq. 2})$$

where k is the intrinsic permeability of the porous medium, p is the fluid density, g is the gravitational acceleration, and $\mu(T)$ is the dynamic viscosity of the pore fluid.

Intrinsic permeability is independent of temperature, as it depends only on the pore structure of the soil, whereas fluid density varies only slightly over the investigated temperature range. Therefore, the increase in hydraulic conductivity with temperature is primarily attributed to the reduction in fluid viscosity. As the temperature increases, the viscosity decreases, resulting in a modest increase in hydraulic conductivity. However, the magnitude of this effect is relatively small for silty sand and is not expected to significantly alter advective transport compared with other processes.

5) Simulation of ammonium migration through QB soils into the underlying soils and groundwater

The landfill site was simulated using data from technical documents and stratigraphic profiles of the study area (Nghie et al., 2017). These include a 20-year operation period (2030–2050), an underlying soil with a 13 m sand layer, a groundwater table at ~14 m depth, a total aquitard thickness of 27 m, and an ammonium concentration in leachate of 50 mg L^{-1} . The design assumptions applied in the modeling include density (1.9 g cm^{-3}), hydraulic conductivity ($6.5 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$), diffusion coefficient ($7.0 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$), and porosity (0.4). An additional assumption of an aquifer porosity of 0.3 was used. The simulation of ammonium migration from wastewater into groundwater was implemented, enclosed with an initial ammonium concentration of 50 mg L^{-1} and the transport parameters of the sandy layer mentioned above in the previous subsections.

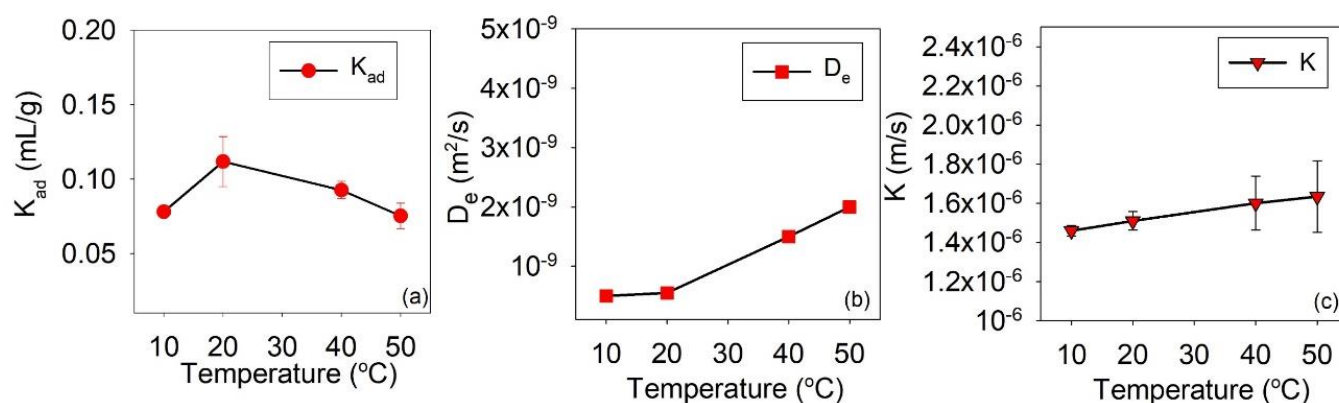


Figure 9 Effect of temperature on ammonium transport coefficients.

The simulated breakthrough curves of the ammonium concentration in the aquifers with an elapsed time of 20 years are shown in Figure 10. These curves reveal a complex and nonmonotonic dependence of ammonium transport on temperature. Although the hydraulic conductivity and effective diffusion coefficient generally increase with temperature, the breakthrough behavior does not follow a simple trend. Notably, the earliest breakthrough is observed at 50 °C, whereas the slowest breakthrough occurs at 20 °C. To fully interpret these shifts, it is essential to distinguish between the specific roles of physical transport (K , D_e) and chemical retention via the apparent K_{ad} . Our POLLUTE simulation demonstrates that this nonmonotonic behavior is driven by a dynamic shift in the dominant regulatory mechanism across different thermal stages.

At 50 °C, the aquifer NH_4^+ concentration reached 0.001 mg L^{-1} after approximately 12.5 years, whereas the same threshold was detected at 15.8 years at 20 °C. In this higher thermal range, physical drivers dominate transport; the thermally induced decrease in water viscosity significantly enhances K and D_e . This physical acceleration effectively overrode chemical retardation, driving rapid NH_4^+ migration and leading to an earlier breakthrough.

Conversely, a comparison between the 10 °C and 40 °C scenarios elucidates a reverse trend where chemical attenuation is dominant. The target breakthrough concentration of $0.03 \text{ mg L}^{-1} \text{ NH}_4^+\text{-N}$ was achieved at 13.1 years at 10 °C and at 13.9 years at 40 °C. At 40 °C, despite the increased permeability, the breakthrough is delayed. This is primarily governed by the higher distribution coefficient at 40 °C than at 10 °C,

which enhances the matrix affinity for NH_4^+ and amplifies the transport retardation.

It should be noted that under field conditions, chemical attenuation can also involve complex microbial processes (such as nitrification, mineralization, microbial assimilation, and oxygen consumption); however, as these processes are outside the scope of this simulation, the chemical retention here is strictly represented by temperature-dependent adsorption (K_{ad}). Additionally, the enhanced diffusion at NH_4^+ causes the solute plume to spread out and dilute longitudinally, further delaying the arrival of the specific concentration threshold. In summary, the simulation successfully separates these mechanisms, proving that the breakthrough timing is governed by a shifting dominance between physical transport acceleration and temperature-dependent chemical retardation.

In accordance with the National Technical Regulation on Groundwater Quality in Vietnam QCVN 09:2023/BTNMT (Ministry of Natural Resources and Environment, 2023), the limit concentration of $\text{NH}_4^+\text{-N}$ in the aquifer is 1 mg L^{-1} . In the 50 °C scenario, a concentration of $\text{NH}_4^+\text{-N}$ of approximately 1 mg L^{-1} is predicted after 13.1 years. This unsanitary landfill has been in operation for almost 6–7 years. However, in the research of Huyen et al. (2024, the concentrations of NH_4^+ in groundwater sampled in 2025 ranged from 1.71 mg L^{-1} to 5.52 mg L^{-1} , exceeding the permissible limit set by QCVN 09:2023/BTNMT. The current high concentration of NH_4^+ in groundwater can be explained by the geological properties of the study area. The groundwater in the study area belongs to the Holocene aquifer system (Thai Binh stratigraphy), where natural concentrations of $\text{NH}_4^+\text{-N}$ vary greatly from 0.1 to 69.8 mg L^{-1} (Tran, 2018).

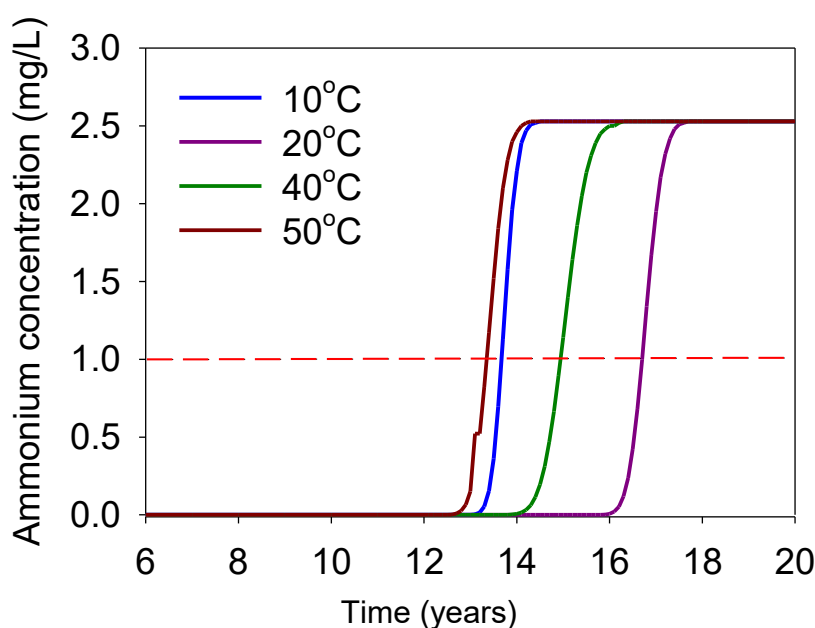


Figure 10 Effect of temperature on ammonium migration into groundwater.

Discussion

On the one hand, the findings of this study, particularly the nonmonotonic breakthrough behavior driven by coupled physical–chemical mechanisms, offer critical insights for the long-term risk assessment of landfill sites. Elevated temperatures generally increase hydraulic conductivity and diffusion while reducing adsorption, thereby decreasing retardation and promoting earlier breakthrough. These findings indicate that increasing temperatures may significantly increase the risk of groundwater contamination at unsanitary landfills under future climate scenarios. When designing groundwater remediation or waste containment liners, environmental engineers must account for temperature fluctuations, especially at higher (40 °C, 50 °C) or lower (10 °C) temperatures. Therefore, effective management of the Quang Binh open dumping landfill requires integrated and climate-adaptive strategies, including stricter enforcement of environmental regulations, the upgrading of landfill infrastructure, such as liners, covers, and leachate treatment systems, and the strengthening of long-term groundwater monitoring systems. Furthermore, improving waste segregation, collection efficiency, and community participation is essential for mitigating contamination risks under increasing thermal variability associated with climate change.

On the other hand, some limitations in this study should be noted. Nonlinear isotherm models, such as the Langmuir and Freundlich models, are typically used to describe adsorption processes, particularly for engineered adsorbents and over wide concentration ranges. Within such a restricted low-concentration case, the adsorption sites remain largely unsaturated, and the isotherm typically presents a linear matrix in which nonlinear models mathematically converge into a linear form. Future work should consider a broader concentration range to assess potential nonlinearity and adsorption capacity limits. Furthermore, this study successfully evaluated initial contaminant infiltration using QB silty sand as the dominant upper layer, and its simulation model faces uncertainties at deeper levels because of a lack of experimental data for stratified soil layers. To address these limitations and improve model accuracy, future work should experimentally characterize additional, deeper soil types to better account for subsurface heterogeneity. Finally, transitioning laboratory-derived apparent distribution coefficients (K_{ad}) to real field-scale applications requires the integration of biochemical complexities. Because ammonium migration in real aquifers is simultaneously driven by active microbial processes, future research must incorporate biological reaction terms into the thermal-transport baseline to accurately capture coupled physical, chemical, and biological attenuation.

Conclusions

The present study investigated the influence of temperature on NH_4^+ transport in sandy soil through laboratory experiments and simplified modeling. The results show that the apparent distribution coefficient (K_{ad}) is in the range of 0.078–0.112 mL g⁻¹ and increases from 10 °C to 20 °C but decreases at higher temperatures (40–50 °C). The effect of temperature on hydraulic conductivity was relatively modest in this temperature range from 1.46–1.63 × 10⁻⁶ m s⁻¹, which is consistent with the behavior of silty sand, where temperature mainly influences fluid viscosity rather than soil structure. In contrast, the effective diffusion coefficients increased more strongly with temperature, indicating that diffusion processes are more sensitive to temperature variations under the conditions investigated. The simulation of ammonium migration from the Quang Binh unsanitary landfill confirmed that ammonium transport is strongly governed by temperature and exhibits nonmonotonic behavior because of coupled physical–chemical transport processes. Higher (50 °C) temperatures accelerate contaminant migration and lead to earlier breakthrough by enhancing diffusion while reducing the apparent adsorption capacity; conversely, the slowest transport occurs at 20 °C because of the maximum chemical retardation effect. Lower temperatures (10 °C) can still trigger relatively early breakthrough because the lower distribution coefficient weakens the ability of the soil to retain ammonium.

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Data availability statement

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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