


A review on the application of nanoporous zeolite for sanitary landfill leachate treatment

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ABSTRACT

This review deals with low-cost nanoporous zeolites for the treatment of sanitary landfill leachate. Organic contaminants and ammoniacal nitrogen are significant parameters in landfill leachate treatment. Adsorption processes are regarded as promising alternative treatment options in this respect. Zeolites are aluminosilicate materials that are widely used in separation, filtration, adsorption and catalysis. Natural zeolite is a low-cost and readily available form of zeolite and is a promising candidate to be used as an ion-exchange material for ammonia and other inorganic pollutant removal from landfill leachate. In this review, adsorption isotherms and kinetic models in batch systems are evaluated and adsorption design parameters of the fixed-bed system are presented. Studies on ammonia removal from landfill leachate via zeolites have been thoroughly investigated. Leachate treatment systems combined with zeolites are presented. Cost of zeolites are also reported in comparison with other adsorbents. The investigated studies demonstrate that activated zeolite can improve the removal of chemical oxygen demand, NH₃-N and colour significantly compared to the case where raw zeolite is used. Moreover, the composite of activated carbon and zeolite is also favorable for ammonia removal according to reported findings, where best adsorptive removal is attained on the composite media (24.39 mg/g).

Key words: ammonia removal, fixed bed system, landfill leachate, low-cost adsorbents, nanoporous materials, zeolite

HIGHLIGHTS

- High ammonium contents in leachate is a serious environmental problem.
- Zeolite is an inexpensive material for the ammonia removal.
- Integration of zeolites to landfill leachate treatment systems increased ammonia removal.
- The column efficiency for ammonia adsorption increased after the regeneration process.
- The activated zeolite can improve the removal of COD and NH₃-N from landfill leachate.

1. INTRODUCTION

Sanitary landfilling is the most common municipal solid waste management practice followed throughout the world. The major problems caused by landfilling are related to the generation of highly contaminated leachates that pose long-term environmental problems. The sanitary landfill leachate composition varies depending on the site, season and age of the landfill. As the landfill age increases, this results in the decrease of organic concentration and the increase of ammonia-nitrogen concentration in landfill leachate. There are three types of leachates which have been classified according to the landfill age as shown in Table 1 and the characteristics of landfill leachate used in the literature is presented in Table 2 (Turan *et al.* 2005a, 2005b; Yalcuk & Ugurlu 2009; Martins *et al.* 2017; Pauzan *et al.* 2020; Scandelai *et al.* 2020). Ammonium is the most significant long-term pollutant present in leachate while its concentration can reach up to 4,000 mg/L (Turan *et al.* 2005a, 2005b; Lin *et al.* 2007; Gunay *et al.* 2008). Conversely, the release of high levels of ammonium into water bodies without proper treatment can have toxic effects on aquatic organisms. Therefore, the treatment of high ammonium contents in the leachate is of great importance to avoid seriously adverse environmental effects.

The biological treatment of landfill leachates has been shown to be very effective in removing organic matter in early stages when the BOD₅/COD ratio of the leachate is high. As a landfill stabilizes in the course of time, the biodegradable organic

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Table 1 | Landfill leachate classification by age (Alvarez-Vazquez *et al.* 2004)

Parameter	Old	Young	Medium
Age (year)	>5.0	<1	1–5
pH	>7.5	<6.5	6.5–7.5
COD (g/L)	<3.0	>15	3.0–1.5
BOD ₅ /COD	<0.1	0.5–1	0.1–0.5
TOC/COD	>0.5	0.3–0.5	0.3–0.5
Ammonium nitrogen (mg/L)	>400	<400	400
Heavy metals (mg/L)	<2.0	>2.0	<2.0
Organic compound	HA+FA	80% VFA	5–30% VFA+HA+FA

BOD, biological oxygen demand-5 days; COD, chemical oxygen demand; FA, fulvic acid; HA, humic acid; TOC, total organic carbon; VFA, volatile fat acids.

Table 2 | Characteristics of landfill leachate used in the literature

Parameter (g/L)	Turan <i>et al.</i> (2005a, 2005b)	Yalcuk & Ugurlu (2009)	Martins <i>et al.</i> (2017)	Pauzan <i>et al.</i> (2020)	Scandelai <i>et al.</i> (2020)
COD	20–50	2.93–14.65	4.35	1.72–2.08	1.05–2.57
TSS	37.5–46	–	–	1.02–11.5	–
TDS	17–35.7	–	–	0.88–1.04	–
Alkalinity as CaCO ₃	12–13	–	10.67	–	–
TKN	1.63–2.75	–	–	2.2–2.4	–
NH ₃ -N	1.03–2.35	1.7–4.01	2.29	1.10–1.89	0.21–0.51
PO ₄ -P	–	0.17–4.01	0.051	–	–
NO ₃ -N	–	0.058–0.112	–	0.235–0.376	0.01–0.084
pH	7.5–8	–	8.2–8.36	8.3–8.5	7.7–8.3

TDS, total dissolved solids; TKN, total Kjeldahl nitrogen; TSS, total suspended solids.

content of the leachate tends to decrease, which result in the loss of the effectiveness of the biological process. In such cases, physico-chemical processes may become one of the most favorable options to be implemented. Several investigators have reported studies on such leachate treatment methods including coagulation-flocculation (Amokrane *et al.* 1997), electro-Fenton method (Gau & Chang 1996), membrane processes (Chianese *et al.* 1999; Visvanathan *et al.* 2006), biological processes (Inanc *et al.* 2000; Loukidou & Zouboulis 2001), fixed and fluidized bed reactors (Gulsen & Turan 2004a, 2004b, 2004c; Turan *et al.* 2005a, 2005b; Karadag *et al.* 2008b) and sequencing batch reactors (Aziz *et al.* 2011). The adsorption process provides an attractive alternative for the treatment of sanitary landfill leachate and low-cost and readily available adsorbents have been used for various applications. Many non-conventional low-cost adsorbents, including natural materials, biosorbents and waste materials from industry and agriculture, have been proposed by several workers. Some of the reported sorbents include clay materials (sepiolite, bentonite, kaolinite), zeolites, siliceous materials (silica beads, alunite, perlite), biosorbents (chitosan, peat, biomass), agricultural wastes and industrial waste products.

Zeolites are microporous (pore size <2 nm) crystalline aluminosilicates that are widely used in separation, filtration, adsorption and catalysis (Corma 1995; Danyliuk *et al.* 2020; Soltys *et al.* 2020). The catalytic performance of zeolites is generally attributed to the existence of a network of micropores with uniform size and shape. However, micropores can also be detrimental to catalytic reactions by limiting the diffusion of reagents and/or products throughout the crystals. One possibility to minimize diffusion limitations is to use zeolite nanocrystals, with a size typically smaller than 0.5 µm (Jacobsen *et al.* 2000; Tosheva & Valtchev 2005). Nanoporous zeolites have negative charges that arise due to isomorphous substitution of Al³⁺ for Si⁴⁺ and its typical unit cell formula is given either as Na₆[(AlO₂)₆(SiO₂)₃₀].24H₂O or (Na₂,K₂,Ca,Mg)₃[(AlO₂)₆(SiO₂)₃₀].24H₂O (Breck 1974). The framework structure may contain linked cages, cavities or channels which are of the right size to allow small molecules to enter as shown in Figure 1. The three-dimensional crystal structure of zeolite contains two-dimensional channels

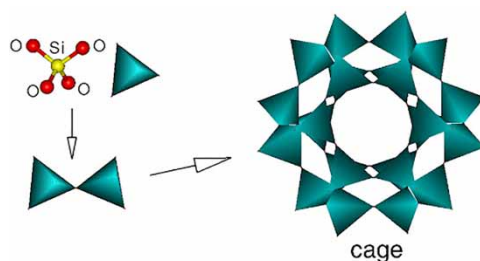


Figure 1 | Scheme of zeolite structure (Bell 2001).

(Mortier & Pearce 1981; Ackley & Yang 1991) which embody some ion-exchangeable cations such as Na^+ , K^+ , Ca^{2+} and Mg^{2+} . These cations can be exchanged with organic and inorganic cations (Ames 1960; Barrer *et al.* 1967; Blanchard *et al.* 1984). Such sorptive properties have been utilized for a variety of purposes such as removal of ammonia (Gaspard *et al.* 1983; Turan & Celik 2003), heavy metals (Semmens & Martin, 1988; Mier *et al.* 2001; Turan *et al.* 2005a, 2005b) and dyes (Meshko *et al.* 2001; Faki *et al.* 2008; Ozdemir *et al.* 2009).

Among many other treatment alternatives, ammonium removal by ion exchange is very attractive especially in case a low-cost exchanger is used. Many researchers have reported that this process is promising due to its low cost and relatively simple application (Baykal & Guven 1997; Nguyen & Tanner 1998; Karadag *et al.* 2006). Clinoptilolite is a natural aluminosilicate zeolite mineral that contains exchangeable cations, such as Na^+ , K^+ , Ca^{2+} and Mg^{2+} in its structural framework. Ammonium ions in wastewater can replace these cations during the treatment process (Colella 1999; Townshend *et al.* 2003). Ammonium removal by clinoptilolite can be performed in either batch- or column-wise. Batch studies have been widely preferred by researchers to examine the effects of parameters such as pH, contact time, ammonium concentration, temperature and competitive ions on ammonium removal (Chen *et al.* 2002; Jorgensen & Weatherley 2003). Batch experiments are more convenient to be performed at laboratory scale, while column studies are more suitable for practical applications of continuous pollutant treatment at higher scales. In this paper, the technical feasibility of zeolite material as a low-cost adsorbent for the treatment of sanitary landfill leachate has been reviewed. The review discusses ammonia adsorption capacities and other parameters for nanoporous zeolites, describes ammonia adsorption onto nanoporous zeolite in batch and fixed bed systems, investigates ammonia removal efficiency for landfill leachate treatment systems combined with zeolites and analyses the application costs of zeolites and other low-cost materials.

2. BATCH ADSORPTION STUDIES

2.1. Equilibrium isotherms

Ammonium sorption studies are performed batch-wise to generate rate and equilibrium data. The removal efficiency (%) and the adsorption capacity at equilibrium q_e (mg/g) of adsorbent (zeolite) are as follows, respectively:

$$\text{Removal efficiency (\%)} = (C_i - C_e) / C_i \times 100 \quad (1)$$

$$q_e = (C_i - C_e) V / W \quad (2)$$

where C_i and C_e are the initial and equilibrium solution concentrations (mg/L), respectively, V is the volume of the solutions (L) and W is the weight of the adsorbent used (g). The widely used Langmuir isotherm (Langmuir 1918) has been found to represent adsorption behavior well in many real sorption processes and is expressed as:

$$q_e = QbC_e / (1 + bC_e) \quad (3)$$

where Q (mg/g) is the maximum amount of the adsorbate per unit weight of adsorbent to form a complete monolayer coverage on the surface bound at high equilibrium adsorbate concentration C_e , and b is the Langmuir constant related to the affinity of binding sites (L/mg). The well known Freundlich isotherm (Freundlich 1906) used for isothermal adsorption is a special case utilized for heterogeneous surface energy systems, where the energy term in the Langmuir equation is

substituted with a function of surface coverage strictly due to variation of the sorption, and the Freundlich equation is given as:

$$q_e = Q_f C_e^{1/n} \quad (4)$$

where Q_f is roughly an indicator of the adsorption capacity and $1/n$ of the adsorption intensity.

The magnitude of the exponent $1/n$ gives an indication of the favorability of adsorption. Values, $n > 1$ represent favorable adsorption condition (McKay *et al.* 1982). The three-parameter Koble–Corrigan (KeC) model is the combination of Langmuir and Freundlich models and is given by Equation (5) while this model is valid provided that $m > 1$ (Aksu & Isoglu 2005):

$$q_e = AC_e^m / (1 + C_e^m) \quad (5)$$

Redlich–Peterson (ReP) is a three-constant model, which has been proposed to improve the fit by Langmuir and Freundlich models. Equation (6) reduces to a linear isotherm at low surface coverage, to the Freundlich isotherm at high adsorbate concentration and to the Langmuir isotherm when $\beta = 1$ (Stephen *et al.* 2003):

$$q_e = K_{RP} C_e / (1 + \alpha_{RP} C_e^\beta) \quad (6)$$

where K_{RP} , α_{RP} and β are the ReP parameters and β is between 0 and 1. The derivation of the Temkin isotherm assumes that the fall in the heat of adsorption is linear rather than logarithmic, as implied in the Freundlich equation and the Temkin isotherm is given as follows (Fu *et al.* 1994):

$$q_e = A + B \ln C_e \quad (7)$$

where A and B are isotherm constants.

2.2. Kinetics and thermodynamics

In order to investigate the mechanism of adsorption, the pseudo-first-order adsorption, the pseudo-second-order adsorption and the intraparticle diffusion models are used to test dynamical experimental data. The first-order rate expression of Lagergren (Lagergren 1898) is given as:

$$\log(q_e - q) = \log q_e - k_1 t / 2.303 \quad (8)$$

where q_e and q are the amounts of solute adsorbed on adsorbent (mg/g) at equilibrium and at time t , respectively and k_1 is the rate constant of first-order adsorption (1/min). The slopes and intercepts of plots of $\log(q_e - q)$ vs. t are used to determine the first-order rate constant k_1 . In many cases the first-order equation of Lagergren does not fit well to the whole range of contact time and is generally applicable over the initial stage of the adsorption processes (McKay & Ho 1999a). The second-order kinetic model (McKay & Ho 1999b) is expressed as:

$$t/q = 1/(k_2 q_e^2) - t/q_e \quad (9)$$

where k_2 (g/mg min) is the rate constant of second-order adsorption and $h = k_2 q_e^2$ is the initial adsorption rate (mg/g min). The slopes and intercepts of plots of t/q vs. t are used to calculate the second-order rate constant k_2 and q_e . This model is more likely to predict the behavior over the whole range of adsorption. The intraparticle diffusion equation can be described as suggested by Weber & Morris (1963):

$$q_t = k_d t^{0.5} + I \quad (10)$$

where q_t is the adsorption capacity (mg/g) of the adsorbent at adsorption time t , q_t is the desorption capacity (mg/g) of the adsorbent at desorption time t , k_d is the rate constant of intraparticle diffusion (mg/(g min^{0.5})) and I is a constant related to the thickness of the boundary layer. The pseudo-second-order rate constant of solute adsorption is expressed as a function of

temperature by the Arrhenius type relationship:

$$\ln k = \ln A - E_a/RT \quad (11)$$

where E_a is the Arrhenius activation energy of sorption, representing the minimum energy that reactants must have for the reaction to proceed, A is the Arrhenius factor, R is the gas constant and (8.314 J/(mol K)) and T is the solution temperature. The thermodynamic parameters such as change in free energy (ΔG°), enthalpy (ΔH°) and entropy (ΔS°) are determined using the following equations (Catena & Bright 1989):

$$K_C = C_e/C_{Ae} \quad (12)$$

$$\Delta G^\circ = -RT \ln K_C \quad (13)$$

$$\log K_C = \Delta S^\circ/(2.303 R) - \Delta H^\circ/(2.303 RT) \quad (14)$$

where K_C is the equilibrium constant, C_{Ae} is the amount of adsorbate (g) adsorbed on the adsorbent per L of the solution at equilibrium, C_e is the equilibrium concentration (g/L) of the adsorbate in the solution, T is the solution temperature (K) and R is the gas constant. ΔH° and ΔS° are calculated from the slope and intercept of van 't Hoff plots of $\log K_C$ vs. $1/T$. The magnitude of activation energy gives an idea about the type of adsorption i.e., whether it is physical or chemical. Generally, the magnitude of the change in free energy for physisorption is between -20 and 0 kJ/mol; chemisorption has a range of -80 to -400 kJ/mol (Nollet *et al.* 2003). The negative values of the standard enthalpy change (ΔH°) indicate that the interaction of the adsorbate with adsorbent is exothermic in nature.

3. COLUMN ADSORPTION STUDIES

Adsorption performance of fixed bed systems can be evaluated via by calculating bed volumes (BV) at breakthrough point ($C/C_o=0.1$). The breakthrough curves are constructed by plotting the normalized effluent concentration (C/C_o) versus time (t) or BV. The BV and the empty bed contact time (EBCT) at the fixed-bed column are defined as follows, respectively:

$$BV = V_F/V_R = Q_t/V_R \quad (15)$$

$$EBCT = V_R/Q \quad (16)$$

where V_F is the total volume of wastewater treated during the adsorption process at time t (L), V_R is the fixed-bed volume of zeolite (L), C_o is the influent concentration (mg/L), C is the effluent concentration at time t (mg/L), Q is the feed flow rate (L/min) and t is the service time (min). The formation and the movement of the adsorption zone can be evaluated numerically (Benfield *et al.* 1982; Kundu & Gupta 2005). The time required for the adsorption zone to become established and move completely out of the bed at exhaust time is:

$$t_{Exh} = V_{Exh}/Q = BV_{Exh}EBCT \quad (17)$$

The rate at which the adsorption zone (U_z , cm/min) is moving up or down through the bed is:

$$U_z = h_z/t_z = h/(t_{Exh} - t_f) \quad (18)$$

From Equation (18), the height of the adsorption zone (h_z) is obtained:

$$h_z = h(t_z)/(t_{Exh} - t_f) \quad (19)$$

where V_{Exh} is the total volume of wastewater treated in the zeolite column at exhaust time (L), h_z is the height of adsorption zone (cm), h is the total bed height (cm), and t_f is the time required for the adsorption zone to initially form (min). The t_f value

can be found as follows:

$$t_f = (1 - F)t_z \quad (20)$$

At breakthrough, the fraction (F) of adsorbent present in the adsorption zone still possessing the ability to remove solute is:

$$F = S_z/S_{\max} = \int_{V_b}^{V_{\text{Exh}}} (C_o - C)dV/C_o(V_{\text{Exh}} - V_b) \quad (21)$$

where V_b is the total volume of the wastewater treated to the breakthrough point (L), S_z is the amount of solute that has been removed by the adsorption zone from breakthrough to exhaustion and S_{\max} is the amount of solute removed by the adsorption zone when completely exhausted. The percentage of the saturation of total column at breakthrough point is:

$$\% \text{ saturation} = (h + (F - 1)h_z) \times 100/h \quad (22)$$

4. MODIFIED ZEOLITES

The use of zeolite minerals in environmental applications is gaining new research interests mainly due to their physico-chemical properties, wide distribution all over the world and the convenience of its modification (Li *et al.* 2011). Several modification methods can be applied to enhance the ammonium adsorption capacity of zeolite. Some modification processes reported in the literature are given as follows:

Heat-activated zeolite (HAZ): Zeolite was activated at 150 for 3 h. Batch study experiments were performed to identify the optimum zeolite dosage and the optimum pH of leachate (Aziz *et al.* 2020). The granular zeolite was filtered to a final working size between 2 and 4 mm. Zeolite was weighed, then cleaned with distilled water and dried in an oven at 105 °C for 2 h. After that, it was heated in a muffle furnace at 150 °C for 3 h and afterwards conditioned in a desiccator for 2 h to obtain the HAZ. The activation process was repeated at two different temperatures namely 200 °C and 250 °C for other batch studies.

Sodium-natural zeolite (SNZ): Natural zeolite (NZ) was crushed and sieved through 200–230 mesh sieve. The zeolite powder was washed with distilled water to remove undesirable materials and dried at 100 °C for 24 h and then modified with sodium chloride. The suspension was stirred in a 500 ml conical flask at 90 °C using a magnetic stirrer water bath at a rate of 120 rpm for 2 h. Subsequently, the suspension was filtered and washed with distilled water. The wet modified material was dried at 100 °C in an oven for 24 h (Alshameri *et al.* 2014).

Silicate-carbon modified zeolite (SCMZ): SCMZ was used for ammonium removal from drinking water (Li *et al.* 2011). The modification process applied in the preparation of SCMZ consists of the following steps: In the first step; the clinoptilolite powder (74 µm) was repeatedly washed with tap water and then dried at 100 °C for 4 h. In the second step; zeolite was dried and 1,000 g of the dry zeolite was dispersed into 1 L sodium chloride solution (2 mol/L) that was prepared using tap water and stirring for 12 h. The sample was repeatedly washed with tap water and then dried at 100 °C for 4 h. Finally, the dried sample was ground and sieved to 74 µm again, and designated as sample A. In the final step; sample A, Na₂SiO₃ and powdered activated carbon were mixed at weight/weight ratio of 100:9:2, and mixed evenly; then, 10% tap water (weight/weight ratio) was added and stirred again. The mixture was shaped into a cylinder (D = 4mm, H = 8mm) by an extrusion method and then dried at 100 °C for 2 h and calcined in a muffled furnace at 500 °C for 2 h and the SCMZ filter was obtained.

Calcium formed clinoptilolite (CaY): A modified clinoptilolite zeolite-Ca²⁺-formed material was prepared for the removal of ammonium ions from aqueous solutions (Ji *et al.* 2007). The chosen clinoptilolite was ground and sieved into 0.425–0.970 mm mesh (between 20 and 40 mesh) particle size and then washed twice with distilled water (volume ratio of liquid/solid 3:1) to remove any non-adhesive impurities and small particles. NaY was gained by treating the samples three times with saturated NaCl solution at boiling point for 2 h, and then changed into NH₄⁺-formed clinoptilolite (NH₄Y) by washing it with 1 mol/l NH₄Cl solution for 20 min at room temperature. Finally, CaY was prepared through washing the NH₄Y with Ca(OH)₂ solution at boiling point for 2–3 h.

5. APPLICATION OF BATCH ADSORPTION SYSTEMS ON LANDFILL LEACHATE

An overview of the nanoporous zeolites utilized for the removal of ammonia from sanitary landfill leachate is presented along with significant parameters like adsorption capacities and the experimental conditions used in the batch adsorption systems (Table 3). The feasibility of using natural raw zeolite to remove ammonia in the treatment of leachate from a pilot-scale composting plant for vegetable greenhouse solid waste was studied using batch (Liu 2000; Liu & Lo 2001a) and column (Liu 2000; Liu & Lo 2001b, 2001c) systems. It was observed that ammonium adsorption increased significantly with decreasing zeolite particle size for all tests and the adsorption capacities ranged from 14.35–17.81 mg N/g. Otal *et al.* (2002) used two synthetic zeolites for the decontamination of a highly contaminated municipal waste landfill leachate. Zeolites, especially CV-Z, clearly led to a strong reduction in the leachate nitrogen content. In addition, biological treatment of landfill leachate usually resulted in low COD removals because of high COD levels, high ammonium-N content and the presence of toxic compounds. Pretreated leachate was subjected to adsorbent supplemented biological treatment in an aeration tank operated in fed-batch mode. COD and NH₄-N removal performances of powdered activated carbon (PAC) and powdered zeolite (PZ) were compared during biological treatment. Ammonium-N removals were 30 and 40% with PAC and zeolite concentrations of 5 g/L, respectively at the end of 30 h of fed-batch operation (Kargi & Pamukoglu 2003, 2004).

Recently, the potential of natural Chinese clinoptilolite for ammonia removal from the leachate solution of sewage sludge was investigated (Wang *et al.* 2006) and the maximum adsorption capacity of the clinoptilolite, for ammonium concentration ranging from 11.12 to 115.16 mg/L NH₄⁺ N in leachate solution, was reported as 1.74 mg/g NH₄⁺ N. Karadag *et al.* (2008a) studied the removal of ammonium ion (NH₄⁺) from landfill leachate (Odayeri sanitary landfill, Istanbul) using Gordes (Turkish) clinoptilolite in both batch and column experiments and the chemical characteristics of clinoptilolite is given in Table 4. The equilibrium was reached at 3 h and the highest amount of the ammonium exchanged was 20.37 mg/g for the concentration of 3,750 mg/L. At C/C₀ value of 0.1 (ammonia removal of 90%), the operating time was 20 and 28 h for natural and preconditioned clinoptilolite, respectively. COD and ammoniacal nitrogen have always been the crucially problematic parameters in landfill leachate treatment. Halim *et al.* (2006, 2010a) investigated the adsorption properties of ammoniacal nitrogen and COD in semi-aerobic leachate on zeolite, activated carbon and a new composite media. This composite adsorbent contained 45.94% zeolite, 15.31% limestone, 4.38% activated carbon and rice husk carbon and 30% of ordinary Portland cement (OPC) which was used as a binder. Best ammonia adsorption was obtained on composite media (24.39 mg/g) (Table 3), followed by zeolite (17.45 mg/g) and activated carbon (6.08 mg/g).

Table 3 | Ammonia adsorption capacities and other parameters for zeolites in the batch systems

Adsorbent	Concentration range (mg/L)	pH	Adsorption capacity (mg/g)	References
Canadian zeolite	25–200	8.75	14.4–17.8	Liu & Lo (2001a)
Powdered zeolite	290–340	12	–	Kargi & Pamukoglu (2004)
Chinese clinoptilolite	11–115	7–8	1.74	Wang <i>et al.</i> (2006)
Turkish clinoptilolite	200–3,750	4–10	20.37	Karadag <i>et al.</i> (2008a)
Zeolite-carbon (Z-C)	1,890	8.29	24.39	Halim <i>et al.</i> (2006, 2010a)
Malaysian zeolite	500–1,100	2–12	21.01	Aziz <i>et al.</i> (2010)
Heat-activated zeolite	1,080	8.09	32.8	Aziz <i>et al.</i> (2020)
Turkish clinoptilolite	263–1,364	2–8	7.8–9.1	Temel & Kuleyin (2016)
Turkish clinoptilolite	263–1,364	2–8	8.68	Temel <i>et al.</i> (2021)
Synt.zeolite (geopolymer)	10–1,000	4–8	21.07	Luukkonen <i>et al.</i> (2016)
Cuban zeolite	2,292	7–8.2	10.8	Martins <i>et al.</i> (2017)
Ca, Na-treated zeolite	78–2,805	8–8.5	12.1	Vollprecht <i>et al.</i> (2019)
Natural/synthetic zeolite	1,104–1,890	8–8.5	6.9–17.45	Pauzan <i>et al.</i> (2020)
Malaysian zeolite	3,125–3,782	8–10	–	Hamid <i>et al.</i> (2020)
Greek zeolite	100–600	6–10	3.59	Genethliou <i>et al.</i> (2021)
Malaysian zeolite	406.68	7	–	Detho <i>et al.</i> (2021)

Table 4 | Chemical composition of nanoporous zeolites in the literature

Component (wt %)	Karadag <i>et al.</i> (2008a)	Martins <i>et al.</i> (2017)	Hamid <i>et al.</i> (2020)	Scandela <i>et al.</i> (2020)	Genethliou <i>et al.</i> (2021)
SiO ₂	74.4	68.0	71.8	74.68	69.62
Al ₂ O ₃	11.5	12.0	12.63	11.97	13.62
Fe ₂ O ₃	1.1	1.11	1.43	2.03	0.75
K ₂ O	5.0	1.40	2.56	2.73	2.94
MgO	0.5	0.80	0.61	0.96	0.90
Na ₂ O	0.6	2.67	0.93	1.39	0.55
CaO	2.0	0.98	2.11	4.31	3.28
TiO ₂	0.1	0.37	0.13	0.34	0.11
MnO	<0.001	–	0.03	–	–
P ₂ O ₅	0.02	0.03	0.02	0.06	–
LOI ^a	5.85	12.64	–	–	8.23

^aLoss of ignition.

Leachate generated from one of the old landfills in Malaysia contains high concentrations of colour, COD, iron and ammoniacal species. The ability of activated carbon-zeolite mixtures as an adsorbent was investigated and 21.01 mg/g of ammoniacal nitrogen was removed by a mixture of activated carbon and zeolite (Aziz *et al.* 2010). In addition, the potential use of raw zeolite and heated activated zeolite in the abatement of COD, NH₃-N and colour from leachate was examined (Aziz *et al.* 2020). Zeolite was activated using different temperatures, namely at 150 °C, 200 °C and 250 °C for 3 h. The optimum pH for NH₃-N was 7 with a percentage removal of 55.8% while better abatement of COD and colour was obtained at pH 4 with a percentage removal of 24.3% and 73.8%, respectively. The capacity of the zeolite before and after heat activation was reported as 41.30 cmol/kg and 181.90 cmol/kg, respectively. SEM analysis of zeolite after heat activation showed an increase in the displacement between the crystal structures with enlarged pore size, which is marked by the arrows in Figure 2.

The removal of NH₄⁺-N from landfill leachate using natural Turkish zeolite by adsorption process was investigated (Temel & Kuleyin 2016). The optimum conditions in the adsorption process were found to be as follows: 60 min contact time, 100 g/L adsorbent dosage, 200 rpm agitation speed, 263.2 mg/L initial concentration and –20/+35 mesh particle size. Also, the values of Gibbs free energy (ΔG°), enthalpy (ΔH°) and entropy of activation (ΔS°) were 5.7113–6.5018 kJ/mol, –8.5415 and 8.8209 J/(mol K), respectively. In addition, multilayer perceptron (MLP) artificial neural network was utilized to predict the adsorption rate of ammonium on zeolite (Temel *et al.* 2021). Recently, Aydın & Kuleyin (2011) studied the capacity of natural Turkish zeolite for NH₄⁺ N removal from landfill leachate and Langmuir isotherm model was found to best represent the data for NH₄⁺ N. Ammonium ion-exchange performance of the NZ was investigated in both batch and column studies and ammonium removal increased with increasing zeolite dosage from 25 to 150 g/L while optimum pH was found as 7.1. In the column studies, the total ammonium removal percentage during 180 min operation time decreased with the flow rate ranging from 4 to 9 mL/min (Ye *et al.* 2015).

Geopolymer, which is an amorphous analogue of zeolite and thus possesses similar cation-exchange properties, was synthesized from metakaolin and applied to remove NH₄⁺-N from model solutions and landfill leachate (Luukkonen *et al.* 2016). The synthesis procedure of geopolymer is illustrated in Figure 3. The maximum NH₄⁺-N removal capacity of the geopolymer was found to be 21.07 mg/g (Table 3). A small-scale column experiment with landfill leachate was performed at a flow rate of 3 mL/min (4 BV/h) and 4 h, respectively (Table 5). The saturation–regeneration cycle was repeated three times. The process consisted of ammonium nitrogen adsorption from raw leachate followed by zeolite regeneration via nitrification and next, initial adsorptive capacity of zeolite was evaluated (Martins *et al.* 2017). The adsorptive capacity (q) was reduced by only 4.55% after regeneration from $q = 10.80 \pm 2.14$ mg NH₄⁺-N/g_{zeolite} to 10.32 ± 0.74 mg NH₄⁺-N/g_{zeolite}. Regeneration by nitrification was performed in 72 h, where main product was nitrite. de Paula Couto *et al.* studied the ammonia–nitrogen removal by aluminosilicates from pretreated landfill leachate using three types of commercial clays and one commercial zeolite (de Paula Couto *et al.* 2017). The Langmuir model was adequate to describe the ion-exchange equilibrium and the sorption kinetics fit the pseudo-second-order kinetic model.

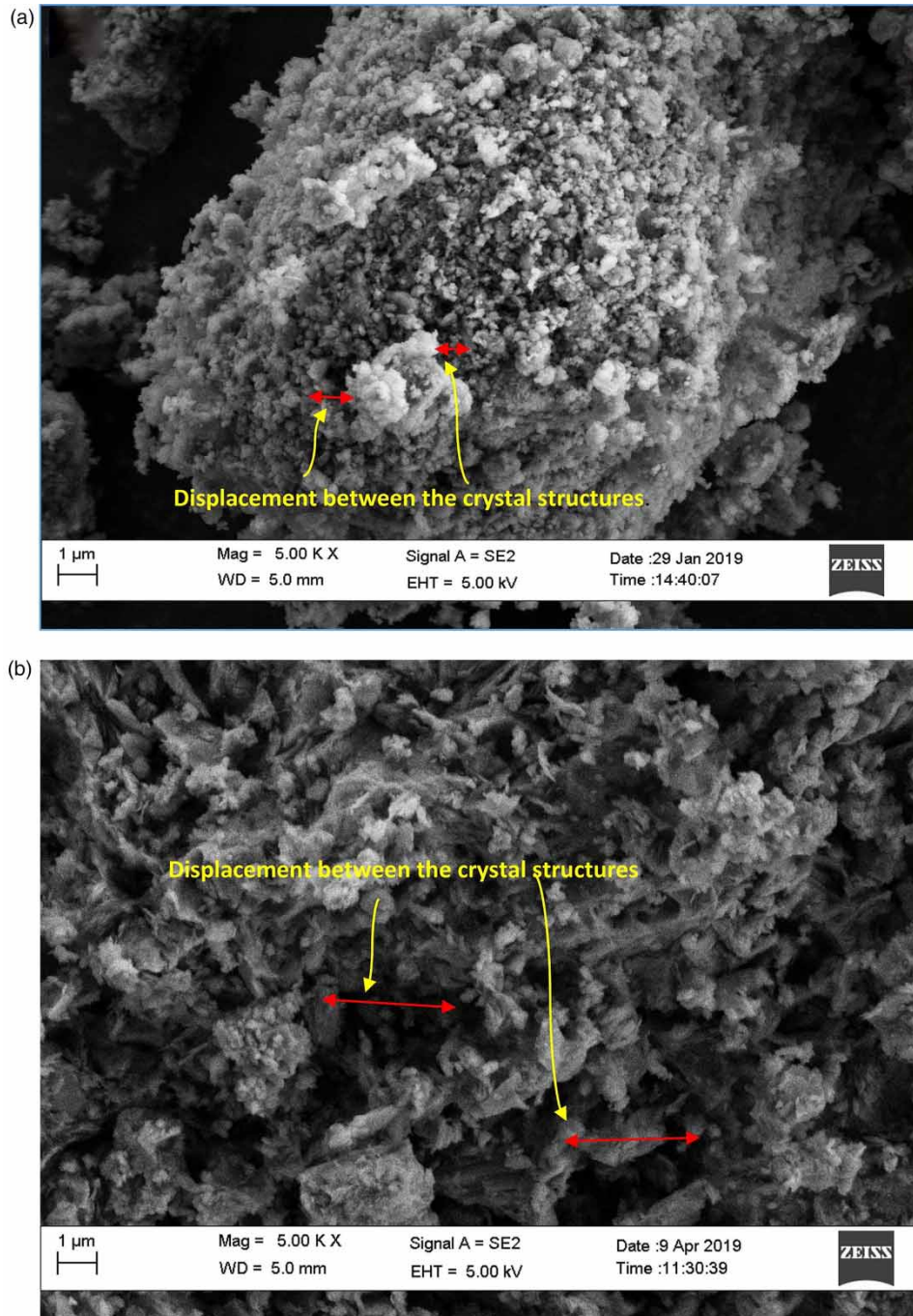


Figure 2 | SEM results for (a) raw zeolite, (b) activated zeolite heated at 150 °C (Aziz *et al.* 2020).

Vollprecht *et al.* (2019) conducted laboratory-scale experiments regarding the sorption of NH_4^+ from landfill leachates using natural and modified clinoptilolite to assess the applicability of the innovative ion-exchanger loop stripping (ILS) process for ammonium recovery. Between 13 and 61% of the dissolved NH_4^+ was adsorbed to the clinoptilolite. Recently, Morris *et al.* (2019) employed four low-cost materials, oyster shells, pumice stone, sand and zeolite as adsorbents in a batch system for the removal of ammonia, phosphate and nitrate from landfill leachate. In addition, oyster shells and pumice stone, were also employed as adsorbents in a fixed-bed column using bed height of 20 cm with a flow rate of 5 mL/min.

Advanced oxidation processes based on ozonation, UV solar radiation, hydrogen peroxide and persulfate for the complete treatment of a specific landfill leachate was tested (Poblete *et al.* 2019). As a post-treatment of the advanced oxidation process,

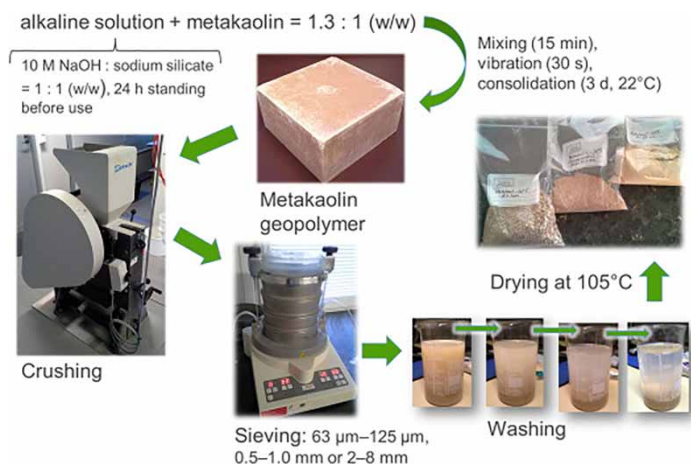


Figure 3 | A pictorial presentation of the synthesis procedure of geopolymer (Luukkonen *et al.* 2016).

Table 5 | Ammonia removal efficiency and other parameters for zeolites in the fixed bed systems

Adsorbent	Concentration range (mg/L)	Flow rate (mL/min)	Removal efficiency (%)	References
Canadian zeolite	25–200	8.3	98	Liu & Lo (2001b)
Canadian zeolite	25–200	8.3	95	Liu & Lo (2001c)
Turkish clinoptilolite	410–830	6.9	>90	Turan <i>et al.</i> (2005a, 2005b)
Turkish clinoptilolite	100–400	21	>90	Karadag <i>et al.</i> (2008a)
Turkish clinoptilolite	400–3,000	21	>90	Karadag <i>et al.</i> (2008b)
Turkish zeolite	122 ± 27	6.94	62–49	Yalcuk & Ugurlu (2009)
Zeolite-carbon (Z-C)	1,640	8	93.7	Halim <i>et al.</i> (2010b)
Activated carbon-zeolite	500	20	70	Aziz <i>et al.</i> (2010)
Synt. zeolite (geopolymer)	700	3	65	Luukkonen <i>et al.</i> (2016)
Czechoslovakian zeolite	1,800 ± 50	–	96	Lim <i>et al.</i> (2016)
Zeolite-slag hybrid subst.	97 ± 27.6	20.8	60–70	He <i>et al.</i> (2017)
Natural zeolite	25–500	1	90	Scandelai <i>et al.</i> (2020)
Turkish clinoptilolite	1,384	2.5–10	99	Temel <i>et al.</i> (2021)

an additional adsorption process was carried out using an NZ and 36, 99 and 18% reductions were observed for COD, ammonium and chloride, respectively. Ammonia removal from landfill leachate using natural and synthetic zeolites was investigated, where response surface methodology approach based on a three-factor three-level central composite design was applied to compare and optimize the removal of $\text{NH}_3\text{-N}$ from landfill leachate (Pauzan *et al.* 2020). Under optimized conditions, clinoptilolite (2 g/L, 50 µm, and 50%) and Sigma 96,096 (4 g/L, 150 µm, and 50%) effectively removed 58.2% and 37.8% of $\text{NH}_3\text{-N}$, respectively. The behavior of a novel zeolite augmented on the electrocoagulation process (ZAEP) using an aluminum electrode in the removal of high-strength concentration ammonia (3,471 mg/L) from landfill leachate was examined (Hamid *et al.* 2020). A response surfaces methodology (RSM) through central composite designs (CCD) was used to optimize the treatment process and the following operation conditions were found to be optimum: Zeolite dosage of 105 g/L, the current density of 600 A/m², electrolysis duration of 60 min, and pH 8.20.

Natural zeolite with maximum adsorption capacity of 3.59 mg/g was used for the simultaneous removal of ammonium nitrogen ($\text{NH}_4^+\text{-N}$), dissolved COD (d-COD) and colour from raw sanitary landfill leachate (SLL) (Genethliou *et al.* 2021). Optimum adsorption results were obtained for particle size of 0.930 µm, stirring rate of 1.18 m/s, zeolite dosage of 133 g/L and pH 8. $\text{NH}_4^+\text{-N}$ removal efficiency reached 51.63 ± 0.80% within 2.5 min of contact time. $\text{NH}_4^+\text{-N}$ release from

the saturated zeolite was not completely reversible, suggesting that the zeolite may be used as a slow $\text{NH}_4^+\text{-N}$ releasing fertilizer and an attractive low-cost material for the treatment of SLL. $\text{NH}_4^+\text{-N}$ removal with the regenerated zeolite exceeded 40% of the initial concentration in the fluid within 2.5 min. Ammonium and phosphate in leachate are potential contaminants for both surface and groundwater. Suprihatin *et al.* (2019) aimed to eliminate these pollutants simultaneously by using activated zeolite. While a physically activated zeolite dosage of 120 g/L resulted in the smallest concentration of ammonium residue of 72.6 mg/L and a phosphate residue of 0.37 mg/L, the chemically–physically activated zeolite (dose of 45 g/L) produced an ammonium residue of 198 mg/L and phosphate residue of 0.74 mg/L. Detho *et al.* (2021) studied to find an alternative treatment by combining low-cost adsorbent such as green mussel waste (*Perna viridis*) and ordinary adsorbent media, granular activated carbon and zeolite. The best ratio for hydrophobic (granular activated carbon and green mussel) and hydrophilic (zeolite) media ratio was selected as 7:3 and the leachate concentration of COD was 310 mg/L with 83% reduction and ammonia–nitrogen was 150 mg/L with 63% reduction.

6. APPLICATION OF FIXED BED COLUMN SYSTEMS ON LANDFILL LEACHATE

The removal of ammonia from sanitary landfill leachate in fixed bed columns has been also investigated in the literature. Bench-scale packed zeolite columns were set up and operated to investigate the continuous removal of ammonium ions from compost leachate. Over 98% of the ammonia input was consistently removed for over five BV of compost leachate flowing through the zeolite column (Liu & Lo 2001b) and more than 95% of adsorbed ammonium ions were recovered after using 7–8 BV of the regenerating solution (Liu & Lo 2001c) (Table 5). The adsorption–regeneration time ratio was approximately 5:1. High concentration of potassium ions in the composting leachate competed with NH_4^+ ions for the exchange sites, resulting in a reduction in the efficiencies of ammonia removal and zeolite column regeneration.

The use of a combined anaerobic fluidized bed and zeolite fixed bed system in sanitary landfill leachate treatment was investigated (Turan *et al.* 2005a, 2005b). The landfill leachate used in the experiments was obtained once every week from a municipal landfill site which had been under operation since 1995 and characterized by young leachates (Table 2). COD removal was attained up to 90% with increasing organic loading rates (OLRs) as high as 18 g COD/L day after 80 days of operation. Biogas production yield (Y_{gas}) of 0.53 $\text{L}_{\text{gas}}/\text{gCOD}_{\text{rem}}$ was obtained along with methane (CH_4) content of 75%. The anaerobically treated landfill leachate was further treated by a zeolite fixed bed reactor and the ammonia removal was obtained as 90% (Table 5). Karadag *et al.* (2008b) studied the removal of ammonium from municipal landfill leachate using clinoptilolite zeolite in upflow fixed-bed and fluidized-bed columns with different ammonium concentrations. Higher effluent volumes and removal rates were obtained at lower ammonium concentrations and increased expansion ratios in the fluidized-bed column reduced the treatment efficiency.

Treatment of organic pollution, ammonia and heavy metals present in landfill leachate by the use of constructed wetland systems was studied (Yalcuk & Ugurlu 2009). The effect of different bed material (gravel and zeolite surface) was also investigated on subsurface flow constructed wetland systems operated in vertical and horizontal modes. Concentration-based average removal efficiencies for two different vertical flow systems (VF1, VF2) and one horizontal flow system (HF) were 62.3%, 48.9% and 38.3% for $\text{NH}_4^+\text{-N}$; 27.3%, 30.6% and 35.7% for COD; 52.6%, 51.9% and 46.7% for $\text{PO}_4\text{-P}$; 21, 40 and 17% for Fe(III), respectively. Better $\text{NH}_4^+\text{-N}$ removal performance was observed in the vertical system with a zeolite layer. The removal efficiencies of two horizontal subsurface flow constructed wetlands (HSSF CWs, down-flow (F1) and up-flow (F2)) filled with the zeolite–slag hybrid substrate for the rural landfill leachate treatment was investigated (He *et al.* 2017). The constructed wetland operated in horizontal subsurface flow mode is shown in Figure 4. The constructed wetlands were capable of removing COD at a level of 20.5–48.2% (F1) and 18.6–61.2% (F2); $\text{NH}_3\text{-N}$ at a level of 84.0–99.9% (F1) and 93.5–99.2% (F2); TN at a level of 80.3–92.1% (F1) and 80.3–91.2% (F2); and heavy metals at a level of about 90% (F1 and F2). The up-flow constructed wetland (F2) has a higher removal efficiency for the PAH compounds.

The performance of a carbon-mineral composite adsorbent used in a fixed bed column for the removal of ammoniacal nitrogen and aggregate organic pollutant (COD), which are commonly found in landfill leachate, was evaluated (Halim *et al.* 2010b). The breakthrough capacities for ammoniacal nitrogen and COD adsorption were 4.46 and 3.23 mg/g, respectively. The column efficiency for ammoniacal nitrogen adsorption was 86.4 and 90% using fresh and regenerated adsorbents, respectively. An aerobic sequencing batch reactor (ASBR) was proposed for the treatment of locally obtained real landfill leachate with initial ammoniacal nitrogen and COD concentration of 1,800 and 3,200 mg/L, respectively (Lim *et al.* 2016). ASBR could remove 65% of ammoniacal nitrogen and 30% of COD during 7 days of treatment time. After that, an effective

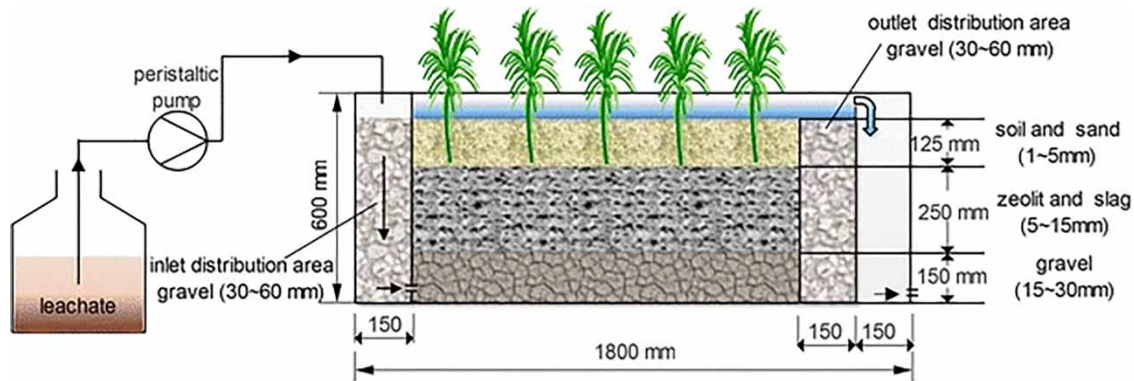


Figure 4 | Schematic diagram of subsurface flow constructed wetland (F2) (He *et al.* 2017).

adsorbent, i.e., zeolite was used as a secondary treatment step for polishing the ammoniacal nitrogen and COD content that is present in leachate while the removal of ammoniacal nitrogen and COD were up to 96 and 43%, respectively.

Over the past few years, supercritical water oxidation (ScWO) has shown great potential for application to landfill leachate treatment, providing substantial organic matter degradation in terms of biochemical oxygen demand (BOD), COD and total organic carbon (TOC). Scandelai *et al.* (2020) evaluates the intensification of the supercritical water oxidation (ScWO) process through ion exchange with zeolite. The zeolite (clinoptilolite) was used without any modification inside a glass column. The ScWO (600 °C)/zeolite system removed 90% of ammoniacal nitrogen (NH₃-N), 100% of nitrite (NO₂-N), 98% of nitrate (NO₃-N), colour and turbidity, 81% of TOC and 74% of COD, suggesting that this system is a promising alternative for leachate treatment.

7. COST ANALYSIS

Zeolites consist of a wide variety of species such as clinoptilolite and chabazite. Clinoptilolite is quite abundant in nature and is readily available from more than 40 NZ species. High ion-exchange capacity and relatively high specific surface areas and more importantly relatively inexpensive prices, make zeolites attractive adsorbents for wastewater treatment. Currently their price range is within ca. US\$0.03– 0.12/kg while the actual price depends on the quality of the mineral (Babel & Kurniawan 2003). Comparatively, the cost of the most inexpensive carbon which is commercially available is about US\$2,000/ton. NZ costs about US\$70/ton, including the cost of its purchase, transport and processing (chemicals, electrical energy and labor required in the process), whereas modified zeolite costs about US\$420/ton (Table 6). That is why, modified zeolite can

Table 6 | Comparative evaluation of costs of zeolite and other adsorbents

Adsorbents	Unit price (US\$/ton)	References
Natural zeolite	70	Babel & Kurniawan (2003)
Surfactant modified zeolite	420	Bowman (2006), Ozdemir (2007)
Bentonite	≤100	Gupta & Suhas (2009)
Montmorillonite clay	40–120	Babel & Kurniawan (2003)
Fuller's earth	40	Atun <i>et al.</i> (2003)
Chitosan	15,430	Babel & Kurniawan (2003)
Peat moss	23	Babel & Kurniawan (2003)
Blast-furnace slag	38	Babel & Kurniawan (2003)
Starch xanthates	1,000	Babel & Kurniawan (2003)
Commercial activated carbon	2,000	Babel & Kurniawan (2003)
Commercial activated carbon	1,500	Gupta & Suhas (2009)
Commercial activated carbon	20,000	Atun <i>et al.</i> (2003)

also be considered as a good alternative to commercially available activated carbon (Bowman 2006; Ozdemir 2007; Faki *et al.* 2008).

Bagasse fly ash, peat, sphagnum moss peat, Fuller's earth, BF slag, bentonite, manganese oxide, Fuller's earth, carbonaceous adsorbent (fertilizer industry waste) are materials costing \leq US\$0.1/kg making them useful low-cost materials as compared to commercial activated carbons (CAC) which normally costs more than US\$1.5/kg (Gupta & Suhas 2009). Among low-cost materials, montmorillonite clay has the largest surface area and the highest cation-exchange capacity. Its current market price (about US\$0.04–0.12/kg) is considered to be 20 times cheaper than that of activated carbon (Babel & Kurniawan 2003). The removal performances of Fuller's earth and CAC for basic blue 9 were compared by Atun *et al.* (2003). Moreover, Fuller's earth is an interesting sorbent since its average price is US\$0.04/kg whereas CAC costs US\$20/kg. Chitosan is produced by alkaline N-deacetylation of chitin, which is widely found in the exoskeleton of shellfish and crustaceans. It was estimated that chitosan could be produced from fish and crustaceans at a market price of US\$15.43/kg (Babel & Kurniawan 2003). Among low-cost materials, zeolite is undoubtedly the most inexpensive alternative adsorbent and is 15 times cheaper than chitosan. Peat moss is a relatively inexpensive material and commercially sold at US\$0.023/kg and blast-furnace slag is sold at US\$38/ton. Besides, the cost of the cheapest CAC is about US\$1,000/ton (Babel & Kurniawan 2003).

8. CONCLUSION

Nanoporous zeolites as low-cost adsorbents have been studied worldwide for the removal of ammonia from sanitary landfill leachate. Zeolite is an inexpensive and locally available material and could be used effectively utilized in place of commercial activated carbon for the ammonia removal from landfill leachate. Synthetic and NZ are important alternatives as adsorbents due to their high ion-exchange and adsorption capacities as well as good thermal and mechanical stabilities. The capacity of the zeolite before and after heat activation was 7.50 mg/g and 32.8 mg/g, respectively. If zeolite performs well in removing ammonia from landfill leachate at low cost, it can be adopted and widely used in sanitary landfill deposits not only to minimize cost inefficiency, but also to improve profitability. Sorptive properties of zeolites have been utilized in previous works for ammonia removal from landfill leachate in batch and fixed-bed modes. The price of zeolites itself is considered very inexpensive, namely about US\$0.03–0.12/kg, depending on the quality of the zeolite itself. Among other low-cost material alternatives, zeolites are the most inexpensive adsorbents. Undoubtedly zeolite as a low-cost adsorbent offers a lot of promising benefits for commercial purpose in the future.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- Ackley, M. W. & Yang, R. T. 1991 *Diffusion in ion-exchanged clinoptilolites*. *AIChE Journal* **37**, 1645–1656. <https://doi.org/10.1002/aic.690371107>.
- Aksu, Z. & Isoglu, I. A. 2005 *Removal of copper(II) ions from aqueous solution by biosorption onto agricultural waste sugar beet pulp*. *Process Biochemistry* **40**, 3031–3044. <https://doi.org/10.1016/j.procbio.2005.02.004>.
- Alshameri, A., Ibrahim, A., Assabri, A. M., Lei, X., Wang, H. & Yan, C. 2014 *The investigation into the ammonium removal performance of Yemeni natural zeolite: modification, ion exchange mechanism, and thermodynamics*. *Powder Technology* **258**, 20–31. <https://doi.org/10.1016/j.powtec.2014.02.063>.
- Alvarez-Vazquez, H., Jefferson, B. & Judd, S. J. 2004 *Membrane bioreactors vs conventional biological treatment of landfill leachate: a brief review*. *Journal of Chemical Technology and Biotechnology* **79**, 1043–1049. <https://doi.org/10.1002/jctb.1072>.
- Ames, L. L. 1960 *The cation sieve properties of clinoptilolite*. *The American Mineralogist* **45**, 689–700.
- Amokrane, A., Comel, C. & Veron, J. 1997 *Landfill leachates pretreatment by coagulation-flocculation*. *Water Research* **31**, 2775–2782. [https://doi.org/10.1016/S0043-1354\(97\)00147-4](https://doi.org/10.1016/S0043-1354(97)00147-4).
- Atun, G., Hisarli, G., Sheldrick, W. S. & Muhler, M. 2003 *Adsorptive removal of methylene blue from colored effluents on Fuller's earth*. *Journal of Colloid Interface Science* **261**, 32–39. [https://doi.org/10.1016/S0021-9797\(03\)00059-6](https://doi.org/10.1016/S0021-9797(03)00059-6).
- Aydın, F. & Kuleyin, A. 2011 *The effect of modification and initial concentration on ammonia removal from leachate by zeolite*. *International Journal of Environmental Chemical Geological Geophysical Engineering* **5**, 336–339. [DOI:10.1007/s12017-011-0097-5](https://doi.org/10.1007/s12017-011-0097-5). <http://www.waset.org/1999.6/10975>.
- Aziz, H. A., Foul, A. A., Isa, M. H. & Hung, Y.-T. 2010 *Physico-chemical treatment of anaerobic landfill leachate using activated carbon and zeolite: batch and column studies*. *International Journal of Environmental Waste Management* **5**, 3–4. [doi:10.1504/IJEW.2010.032008](https://doi.org/10.1504/IJEW.2010.032008).

- Aziz, S. Q., Aziz, H. A., Yusoff, M. S. & Bashir, M. J. K. 2011 Landfill leachate treatment using powdered activated carbon augmented sequencing batch reactor (SBR) process: optimization by response surface methodology. *Journal of Hazardous Materials* **189**, 404–413. <https://doi.org/10.1016/j.jhazmat.2011.02.052>.
- Aziz, H. A., Noor, A. F. M., Keat, Y. W., Alazaiza, M. Y. D. & Hamid, A. A. 2020 Heat activated zeolite for the reduction of ammoniacal nitrogen, colour, and COD in landfill leachate. *International Journal of Environmental Research* **14**, 463–478. <https://doi.org/10.1007/s41742-020-00270-5>.
- Babel, S. & Kurniawan, T. A. 2003 Low-cost adsorbents for heavy metals uptake from contaminated water: a review. *Journal of Hazardous Materials* **97**, 219–243. [https://doi.org/10.1016/S0304-3894\(02\)00263-7](https://doi.org/10.1016/S0304-3894(02)00263-7).
- Barrer, R. M., Paradopoulos, R. & Rees, L. V. C. 1967 Exchange of sodium in clinoptilolite by organic cations. *Journal of Inorganic Nuclear Chemistry* **29**, 2047–2063. [https://doi.org/10.1016/0022-1902\(67\)80466-4](https://doi.org/10.1016/0022-1902(67)80466-4).
- Baykal, B. B. & Guven, D. A. 1997 Performance of clinoptilolite alone and combination with sand filters for the removal of ammonia peaks from domestic wastewater. *Water Science and Technology* **35**, 47. [https://doi.org/10.1016/S0273-1223\(97\)00113-3](https://doi.org/10.1016/S0273-1223(97)00113-3).
- Bell, R. G. 2001 Zeolites – British Zeolite Association. <http://www.bza.org/zeolites/> (accessed 28 October 2021).
- Benefield, L. D., Judkins Jr, J. F. & Weand, B. L. 1982 *Process Chemistry for Water and Wastewater Treatment*. Prentice-Hall, Englewood Cliffs, NJ. ISBN 10: 0137229755/ISBN 13: 9780137229758.
- Blanchard, G., Maunay, M. & Martin, G. 1984 Removal of heavy metals from waters by means of natural zeolites. *Water Research* **18**, 1501–1507. [https://doi.org/10.1016/0043-1354\(84\)90124-6](https://doi.org/10.1016/0043-1354(84)90124-6).
- Bowman, R. S. 2006 *Surfactant-Modified Zeolite (SMZ)-A Versatile, Inexpensive Sorbent for Removing Contaminants From Water*. Research and Development Program Report.
- Breck, D. W. 1974 *Zeolite Molecular Sieves*. John Wiley, NY.
- Catena, G. C. & Bright, F. V. 1989 Thermodynamic study on the effects of β -cyclodextrin inclusion with anilino-naphthalene sulfonates. *Analytical Chemistry* **61**, 905–909. doi:10.1021/ac00183a024.
- Chen, P., Meng-Loong, J. C. & Beiping, Z. 2002 Effects of competitive ions, humic acid and pH on removal of ammonium and phosphorous from synthetic industrial effluent by ion exchange resins. *Waste Management* **22**, 711. doi:10.1016/s0956-053x(02)00051-x.
- Chianese, A., Ranauro, R. & Verdone, N. 1999 Treatment of landfill leachate by reverse osmosis. *Water Research* **33**, 647–652. doi:10.1016/S0043-1354(98)00240-1.
- Colella, C. 1999 Natural zeolites in environmental friendly processes and applications. *Studies in Surface Science and Catalysis* **125**, 641–655. [https://doi.org/10.1016/S0167-2991\(99\)80270-5](https://doi.org/10.1016/S0167-2991(99)80270-5).
- Corma, A. 1995 Inorganic solid acids and their use in acid-catalyzed hydrocarbon reactions. *Chemical Reviews* **95**, 559–614. <https://doi.org/10.1021/cr00035a006>.
- Danyliuk, N., Tomaszewska, J. & Tatarчук, T. 2020 Halloysite nanotubes and halloysite-based composites for environmental and biomedical applications (Review). *Journal of Molecular Liquids* **309**, 113077. <https://doi.org/10.1016/j.molliq.2020.113077>.
- de Paula Couto, R. S., Oliveira, A. F., Guarino, A. W. S., Perez, D. V. & da Costa Marques, M. R. 2017 Removal of ammonia nitrogen from distilled old landfill leachate by adsorption on raw and modified aluminosilicate. *Environmental Technology* **38**, 816–826. <https://doi.org/10.1080/09593330.2016.1212935>.
- Detho, A., Daud, Z., Rosli, M. A., Bin Ridzuan, M. B., Awang, H., Kamaruddin, M. A., Bin Tajarudin, H. A. & Halim, A. A. 2021 COD and ammoniacal nitrogen reduction from stabilized landfill leachate using carbon mineral composite adsorbent. *Desalination and Water Treatment* **210**, 143–151. doi:10.5004/dwt.2021.26500.
- Faki, A., Turan, M., Ozdemir, O. & Turan, A. Z. 2008 Analysis of fixed-bed column adsorption of reactive yellow 176 onto surfactant-modified zeolite. *Industrial & Engineering Chemistry Research* **47**, 6999–7004. <https://doi.org/10.1021/ie800097k>.
- Freundlich, H. 1906 Adsorption solution. *Zeitschrift für Physikalische Chemie* **57**, 384–470.
- Fu, X. C., Shen, W. X. & Yao, T. Y. 1994 *Physical Chemistry*, 4th edn. Higher Education Press, China, pp. 303–321.
- Gaspard, M., Neveu, A. & Matin, G. 1983 Clinoptilolite in drinking water treatment for NH_4^+ removal. *Water Research* **17**, 279–288. [https://doi.org/10.1016/0043-1354\(83\)90181-1](https://doi.org/10.1016/0043-1354(83)90181-1).
- Gau, S. H. & Chang, F. S. 1996 Improved Fenton method to remove recalcitrant organics in landfill leachate. *Water Science and Technology* **34**, 455–462. [https://doi.org/10.1016/S0273-1223\(97\)81411-4](https://doi.org/10.1016/S0273-1223(97)81411-4).
- Genethliou, C., Triantaphyllidou, I. E., Giannakis, D., Papayianni, M., Sygellou, L., Tekerlekopoulou, A. G., Koutsoukos, P. & Vayenas, D. V. 2021 Simultaneous removal of ammonium nitrogen, dissolved chemical oxygen demand and color from sanitary landfill leachate using natural zeolite. *Journal of Hazardous Materials* **406**, 124679. <https://doi.org/10.1016/j.jhazmat.2020.124679>.
- Gulsen, H. & Turan, M. 2004a Startup of an anaerobic fluidized bed reactor for landfill leachate treatment. *Environmental Technology* **25**, 1107–1114. <http://dx.doi.org/10.1080/09593332508618388>.
- Gulsen, H. & Turan, M. 2004b Treatment of sanitary landfill leachate using a combined anaerobic fluidized bed reactor and fenton's oxidation. *Environmental and Engineering Science* **21**, 627–636. <https://doi.org/10.1089/ees.2004.21.627>.
- Gulsen, H. & Turan, M. 2004c Anaerobic treatability of sanitary landfill leachate in a fluidized bed reactor. *Turkish Journal of Engineering and Environmental Science* **28**, 297–305.
- Gunay, A., Karadag, D., Tosun, I. & Ozturk, M. 2008 Use of magnesite as a magnesium source for ammonium removal from leachate. *Journal of Hazardous Materials* (1–3), 156–619. <https://doi.org/10.1016/j.jhazmat.2007.12.067>.

- Gupta, V. K. & Suhas 2009 Application of low-cost adsorbents for dye removal – A review. *Journal of Environmental Management* **90**, 2313–2342. <https://doi.org/10.1016/j.jenvman.2008.11.017>.
- Halim, A. A., Aziz, H. A., Johari, M. A. M. & Ariffin, K. S. 2006 Landfill leachate treatment using combination of hydrophobic–hydrophilic and low cost adsorption materials as a single media. In: *Proceeding of 1st Civil Engineering Colloquium (CEC'06)*. School of Civil Engineering, USM, Nibong Tebal, Penang, Malaysia.
- Halim, A. A., Aziz, H. A., Johari, M. A. M. & Ariffin, K. S. 2010a Comparison study of ammonia and COD adsorption on zeolite, activated carbon and composite materials in landfill leachate treatment. *Desalination* **262**, 31–35. <https://doi.org/10.1016/j.desal.2010.05.036>.
- Halim, A. A., Aziz, H. A., Johari, M. A. M. & Ariffin, K. S. 2010b Ammoniacal nitrogen and COD removal from semi-aerobic landfill leachate using a composite adsorbent: fixed bed column adsorption performance. *Journal of Hazardous Materials* **175**, 960–964. <https://doi.org/10.1016/j.jhazmat.2009.10.103>.
- Hamid, M. A. A., Aziz, H. A., Yusoff, M. S. & Rezan, S. A. 2020 Optimization and analysis of zeolite augmented electrocoagulation process in the reduction of high-strength ammonia in saline landfill leachate. *Water* **12** (247), 2–18. <https://doi.org/10.3390/w12010247>.
- He, H., Duan, Z., Wang, Z. & Yue, B. 2017 The removal efficiency of constructed wetlands filled with the zeolite-slag hybrid substrate for the rural landfill leachate treatment. *Environmental Science and Pollution Research* **24**, 17547–17555. doi:10.1007/s11356-017-9402-x.
- Inanc, B., Calli, B. & Saatci, A. 2000 Characterization and anaerobic treatment of the sanitary landfill leachate in Istanbul. *Water Science and Technology* **41**, 223–230. <https://doi.org/10.2166/wst.2000.0075>.
- Jacobsen, C. J. H., Madsen, C., Janssens, T. V. W., Jakobsen, H. J. & Skibsted, J. 2000 Zeolites by confined space synthesis – characterization of the acid sites in nanosized ZSM-5 by ammonia desorption and $^{27}\text{Al}/^{29}\text{Si}$ -MAS NMR spectroscopy. *Microporous Mesoporous Materials* **39**, 393–401. [https://doi.org/10.1016/S1387-1811\(00\)00215-8](https://doi.org/10.1016/S1387-1811(00)00215-8).
- Ji, Z.-Y., Yuan, J.-S. & Li, X.-G. 2007 Removal of ammonium from wastewater using calcium form clinoptilolite. *Journal of Hazardous Materials* **141**, 483–488. <https://doi.org/10.1016/j.jhazmat.2006.07.010>.
- Jorgensen, T. C. & Weatherley, L. R. 2003 Ammonia removal from wastewater by ion exchange in the presence of organic contaminants. *Water Research* **37**, 1723. [https://doi.org/10.1016/S0043-1354\(02\)00571-7](https://doi.org/10.1016/S0043-1354(02)00571-7).
- Karadag, D., Koc, Y., Turan, M. & Armagan, B. 2006 Removal of ammonium ion from aqueous solution using natural Turkish clinoptilolite. *Journal of Hazardous Materials* **136**, 604–609. <https://doi.org/10.1016/j.jhazmat.2005.12.042>.
- Karadag, D., Tok, S., Akgul, E., Turan, M., Ozturk, M. & Demir, A. 2008a Ammonium removal from sanitary landfill leachate using natural Gordes clinoptilolite. *Journal of Hazardous Materials* **153**, 60–66. <https://doi.org/10.1016/j.jhazmat.2007.08.019>.
- Karadag, D., Akkaya, E., Demir, A., Saral, A., Turan, M. & Ozturk, M. 2008b Ammonium removal from municipal landfill leachate by clinoptilolite bed columns: breakthrough modeling and error analysis. *Industrial & Engineering Chemistry Research* **47**, 9552–9557. <https://doi.org/10.1021/ie800434e>.
- Kargi, F. & Pamukoglu, M. Y. 2003 Simultaneous adsorption and biological treatment of pretreated landfill leachate by fed-batch operation. *Process Biochemistry* **38**, 1413–1420. [https://doi.org/10.1016/S0032-9592\(03\)00030-X](https://doi.org/10.1016/S0032-9592(03)00030-X).
- Kargi, F. & Pamukoglu, M. Y. 2004 Adsorbent supplemented biological treatment of pre-treated landfill leachate by fed-batch operation. *Bioresource Technology* **94**, 285–291. <https://doi.org/10.1016/j.biortech.2004.01.003>.
- Kundu, S. & Gupta, A. K. 2005 Analysis and modeling of fixed bed column operations on As (V) removal by adsorption onto iron oxide-coated cement (IOCC). *Journal of Colloid Interface Science* **290**, 52–60. <https://doi.org/10.1016/j.jcis.2005.04.006>.
- Lagergren, S. 1898 Zur theorie der sogenannten adsorption gelöster stoffe, Kungliga Svenska Vetenskapsakademien. *Handlingar* **24**, 1–39.
- Langmuir, I. 1918 Adsorption of gases on plain surfaces of glass mica platinum. *Journal of American Chemical Society* **40**, 1361–1403.
- Li, M., Zhu, X., Zhu, F., Ren, G., Cao, G. & Song, L. 2011 Application of modified zeolite for ammonium removal from drinking water. *Desalination* **271**, 295–300. <https://doi.org/10.1016/j.desal.2010.12.047>.
- Lim, C. K., Seow, T. W., Neoh, C. H., Nor, M. H. M., Ibrahim, Z., Ware, I. & Sarip, S. H. M. 2016 Treatment of landfill leachate using ASBR combined with zeolite adsorption technology. *3 Biotech* **6**, 1–6. <https://link.springer.com/article/10.1007/s13205-016-0513-8>.
- Lin, L., Chan, G. Y. S., Jiang, B. L. & Lan, C. Y. 2007 Use of ammoniacal nitrogen tolerant microalgae in landfill leachate treatment. *Waste Management* **27**, 1376–1382. <https://doi.org/10.1016/j.wasman.2006.09.001>.
- Liu, C.-H. 2000 A Study on the Utilization on Zeolite for Ammonia Removal From Composting Leachate. MSc thesis, The University of British Columbia, Vancouver, Canada. Available from: <https://open.library.ubc.ca/cIRcle/collections/ubctheses/831/items/1.0058989>.
- Liu, C.-H. & Lo, K. V. 2001a Ammonia removal from composting leachate using zeolite. I. Characterization of the zeolite. *Journal of Environmental Science and Health A* **36**, 1671–1688. <https://doi.org/10.1081/ESE-100106251>.
- Liu, C.-H. & Lo, K. V. 2001b Ammonia removal from compost leachate using zeolite. II. A study using continuous flow packed columns. *Journal of Environmental Science and Health B* **36**, 667–675. <https://doi.org/10.1081/PFC-100106193>.
- Liu, C.-H. & Lo, K. V. 2001c Ammonia removal from compost leachate using zeolite. III. Regeneration of zeolite columns. *Journal of Environmental Science and Health A* **36**, 1825–1843. <https://doi.org/10.1081/ESE-100107432>.
- Loukidou, M. X. & Zouboulis, A. I. 2001 Comparison of two biological treatment processes using attached growth biomass for sanitary landfill leachate treatment. *Environmental Pollution* **111**, 273–281. [https://doi.org/10.1016/S0269-7491\(00\)00069-5](https://doi.org/10.1016/S0269-7491(00)00069-5).
- Luukkonen, T., Sarkkinen, M., Kempainen, K., Rämö, J. & Lassi, U. 2016 Metakaolin geopolymer characterization and application for ammonium removal from model solutions and landfill leachate. *Applied Clay Science* **119**, 266–276. <http://dx.doi.org/10.1016/j.clay.2015.10.027>.

- Martins, T. H., Souza, T. S. O. & Foresti, E. 2017 Ammonium removal from landfill leachate by Clinoptilolite adsorption followed by bioregeneration. *Journal of Environmental Chemical Engineering* **5**, 163–168. <http://dx.doi.org/10.1016/j.jece.2016.11.024>.
- McKay, G. & Ho, Y. S. 1999a The sorption of lead (II) on peat. *Water Research* **33**, 578–584. [https://doi.org/10.1016/S0043-1354\(98\)00207-3](https://doi.org/10.1016/S0043-1354(98)00207-3).
- McKay, G. & Ho, Y. S. 1999b Pseudo-second order model for sorption processes. *Process Biochemistry* **34**, 451–465. [https://doi.org/10.1016/S0032-9592\(98\)00112-5](https://doi.org/10.1016/S0032-9592(98)00112-5).
- McKay, G., Blair, H. S. & Gardner, J. R. 1982 Adsorption of dyes on chitin. I. Equilibrium studies. *Journal of Applied Polymer Science* **27**, 3043–3057. <https://doi.org/10.1002/app.1982.070270827>.
- Meshko, V., Markovska, L., Mincheva, M. & Rodrigues, A. E. 2001 Adsorption of basic dyes on granular activated carbon and natural zeolite. *Water Research* **35**, 3357–3366. [https://doi.org/10.1016/S0043-1354\(01\)00056-2](https://doi.org/10.1016/S0043-1354(01)00056-2).
- Mier, M. V., Callegas, R. L., Gehr, R., Cisneros, B. E. J. & Alvarez, P. 2001 Heavy metal removal with Mexican clinoptilolite: multi component ionic exchange. *Water Research* **35**, 373–378. [https://doi.org/10.1016/S0043-1354\(00\)00270-0](https://doi.org/10.1016/S0043-1354(00)00270-0).
- Morris, S., Garcia-Cabellos, G., Ryan, D., Enright, D. & Enright, A.-M. 2019 Low-cost physicochemical treatment for removal of ammonia, phosphate and nitrate contaminants from landfill leachate. *Journal of Environmental Science and Health A* **54**, 1233–1244. <https://doi.org/10.1080/10934529.2019.1633855>.
- Mortier, W. J. & Pearce, J. R. 1981 Thermal stability of the heulandite type framework: crystal structure of the calcium/ammonium form dehydrate at 483 K. *The American Mineralogist* **66**, 309–314. Online ISSN 1945-3027. Print ISSN 0003-004X.
- Nguyen, M. L. & Tanner, C. C. 1998 Ammonium removal from wastewaters using natural New Zealand Zeolites. *New Zealand Journal of Agricultural Research* **41**, 427–446. <https://doi.org/10.1080/00288233.1998.9513328>.
- Nollet, H., Roels, M., Lutgen, P., Van der Meeren, P. & Verstraete, W. 2003 Removal of PCBs from wastewater using fly ash. *Chemosphere* **53** (6), 655–665. [https://doi.org/10.1016/S0045-6535\(03\)00517-4](https://doi.org/10.1016/S0045-6535(03)00517-4).
- Otal, E., Pereira, C. F., Vilches, L. F. & Quero, X. 2002 Application of synthetic zeolites to the deputation of a waste landfill leachate. In: *Waste Management and the Environment* (Almorza, D., Brebbia, C. A., Sales, D. & Popov, V., eds.). WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK, pp. 142–150. ISBN 1-85312-907-0.
- Ozdemir, O. 2007 *Investigation of Color Removal From Textile Industry Dyehouse Wastewater in Modified Zeolite Fixed-Bed Reactor*. PhD thesis, Istanbul Technical University, Istanbul, Turkey.
- Ozdemir, O., Turan, M., Turan, A. Z., Faki, A. & Engin, A. B. 2009 Feasibility analysis of color removal from textile dyeing wastewater in a fixed-bed column system by surfactant-modified zeolite (SMZ). *Journal of Hazardous Materials* **166**, 647–654. <https://doi.org/10.1016/j.jhazmat.2008.11.123>.
- Pauzan, M. A. B., Puteh, M. H., Yuzir, A., Othman, M. H. D., Wahab, R. A. & Abideen, M. Z. 2020 Optimizing ammonia removal from landfill leachate using natural and synthetic zeolite through statically designed experiment. *Arabian Journal of Science and Engineering* **45**, 3657–3669. <https://doi.org/10.1007/s13369-019-04204-y>.
- Poblete, R., Oller, I., Maldonado, M. I. & Cortes, E. 2019 Improved landfill leachate quality using ozone, UV solar radiation, hydrogen peroxide, persulfate and adsorption processes. *Journal of Environmental Management* **232**, 45–51. <https://doi.org/10.1016/j.jenvman.2018.11.030>.
- Scandelay, A. P. J., Zotesso, J. P., Jegatheesan, V., Cardozo-Filho, L. & Tavares, C. R. G. 2020 Intensification of supercritical water oxidation (ScWO) process for landfill leachate treatment through ion exchange with zeolite. *Waste Management* **101**, 259–267. <https://doi.org/10.1016/j.wasman.2019.10.005>.
- Semmens, M. J. & Martin, W. P. 1988 The influence of pretreatment on the capacity and selectivity of clinoptilolite for metal ions. *Water Research* **22**, 537.
- Soltys, L. M., Mironyuk, I. F., Tatarchuk, T. R. & Tsinurchyn, V. I. 2020 Zeolite-based composites as slow release fertilizers (Review). *Physics and Chemistry of Solid State* **21**, 89–104. <https://doi.org/10.15330/pcss.21.1.89-104>.
- Stephen, J. A., Quan, G., Ronan, M. & Pauline, A. J. 2003 Comparison of optimized isotherm models for basic dye adsorption by kudzu. *Bioresource Technology* **88**, 143–152. [https://doi.org/10.1016/S0960-8524\(02\)00281-X](https://doi.org/10.1016/S0960-8524(02)00281-X).
- Suprihatin, S., Yani, M. & Fitriyani, A. L. 2019 Simultaneous recovery of ammonium and phosphate from leachate by using activated zeolite. *Published under licence by IOP Publishing Ltd*. IOP Conference Series: Earth and Environmental Science, Volume 477, Sustainable Urban Water International Seminar 2019 24th January 2019, Bogor Indonesia.
- Temel, F. A. & Kuleyin, A. 2016 Ammonium removal from landfill leachate using natural zeolite: kinetic, equilibrium, and thermodynamic studies. *Desalination and Water Treatment* **57**, 23873–23892. <http://dx.doi.org/10.1080/19443994.2015.113696>.
- Temel, F. A., Yolcu, Ö. C. & Ayse Kuleyin, A. 2021 A multilayer perceptron-based prediction of ammonium adsorption on zeolite from landfill leachate: batch and column studies. *Journal of Hazardous Materials* **410**, 124670. <https://doi.org/10.1016/j.jhazmat.2020.124670>.
- Tosheva, L. & Valtchev, V. P. 2005 Nanozeolites: synthesis, crystallization mechanism, and applications. *Chemistry of Materials* **17**, 2494–2513. <https://doi.org/10.1021/cm047908z>.
- Townshend, A., Dickinson, K., Dobson, I., Batten, M., Liddle, B. & Coombs, C. 2003 *Development of A Novel Ammonia Filter for Landfill Leachate Treatment*. Final report.
- Turan, M. & Celik, M. S. 2003 Regenerability of Turkish clinoptilolite for use in ammonia removal from drinking water. *Journal of Water Supply: Research and Technology-AQUA* **52**, 59–66. <https://doi.org/10.2166/aqua.2003.0006>.

- Turan, M., Mart, U., Yüksel, B. & Celik, M. S. 2005a Lead removal in fixed-bed columns by zeolite and sepiolite. *Chemosphere* **60**, 1487–1492. <https://doi.org/10.1016/j.chemosphere.2005.02.036>.
- Turan, M., Gulsen, H. & Celik, M. S. 2005b Treatment of landfill leachate by a combined anaerobic fluidized bed and zeolite column system. *Journal of Environmental Engineering* **131**, 815–819. [https://doi.org/10.1061/\(ASCE\)0733-9372\(2005\)131:5\(815\)](https://doi.org/10.1061/(ASCE)0733-9372(2005)131:5(815)).
- Visvanathan, C., Choudhary, M. K., Montalbo, M. T. & Jegatheesan, V. 2006 Landfill leachate treatment using thermophilic membrane bioreactor. *Desalination* **204**, 8–16. <https://doi.org/10.1016/j.desal.2006.02.028>.
- Vollprecht, D., Frühauf, S., Stocker, K. & Ellersdorfer, M. 2019 Ammonium sorption from landfill leachates using natural and modified zeolites: pre-tests for a novel application of the ion exchanger loop stripping process. *Minerals* **9** (471), 1–10. <https://doi.org/10.3390/min9080471>.
- Wang, Y., Liu, S., Xu, Z., Han, T., Chuan, S. & Zhu, T. 2006 Ammonia removal from leachate solution using natural Chinese clinoptilolite. *Journal of Hazardous Materials* **136**, 735–740. <https://doi.org/10.1016/j.jhazmat.2006.01.002>.
- Weber, W. J. & Morris, J. C. 1963 Kinetics of adsorption on carbon from solution. *Journal of Sanitary Engineering Division* **89**, 31–60.
- Yalcuk, A. & Ugurlu, A. 2009 Comparison of horizontal and vertical constructed wetland systems for landfill leachate treatment. *Bioresource Technology* **100**, 2521–2526. <https://doi.org/10.1016/j.biortech.2008.11.029>.
- Ye, Z., Wang, J., Sun, L., Zhang, D. & Zhang, H. 2015 Removal of ammonium from municipal landfill leachate using natural zeolites. *Environmental Technology* **36**, 2919–2925. <https://doi.org/10.1080/09593330.2014.941943>.

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