

Ammonium assists orthophosphate removal from high-strength wastewaters by natural zeolite

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Abstract

Nutrients discharge correlates to eutrophication of receiving waters. Phosphorus (P) and nitrogen (N), if recovered from wastewaters, can be applied to land as essential nutrients for plant growth. This study used natural zeolite in batch and continuous tests to simultaneously remove P and N from orthophosphate and ammonium-nitrogen laden wastewaters at pH 3–11. In P only tests, pH > 9 is favorable to P removal. When ammonium was also present, P removal was significantly enhanced. Ammonium was first adsorbed onto the zeolite via ion exchange to release Ca²⁺ ions from the zeolite lattice. This ion exchange reaction was independent of the presence of P. Then the released Ca²⁺ ions precipitated the dissolved phosphate, which was greatly dependent on the concentration of ammonium. Zeolite column could effectively remove P and N from fermentation liquor with minimal adsorption of volatile fatty acids. Implications to practice of zeolite treatment were discussed.

Keywords Ammonium; Phosphate; Simultaneous removal; Mechanism; Natural zeolite; Fermentation liquor

1. Introduction

Excess discharge of nitrogen (N) and phosphorus (P) to receiving waters yields occurrence of water body eutrophication [1]. Biological nutrient removal (BNR) process is effective to remove nitrogen and phosphorus [2], but it requires expensive supplemented carbon source [3]. Volatile fatty acids (VFAs) produced by anaerobic fermentation of organic wastes are suitable carbon sources for

1 the BNR process [4]. However, the accompanied high levels of nitrogen ($\text{NH}_4^+\text{-N}>400 \text{ mg l}^{-1}$) and
2 phosphorus ($\text{PO}_4^-\text{P}>100 \text{ mg l}^{-1}$) in the fermentation liquor have to be effectively removed [5–7].
3 Cost-effective and simple practice with end products recyclable to land use is welcome to remove N
4 and P in fermentation effluents [8].

5 Zeolite is an aluminosilicate mineral that can be used as ammonium adsorbent at the release of
6 Na^+ , Ca^{2+} , K^+ and/or Mg^{2+} from the crystal framework [9–15]. For instance, Lin *et al.* [16] noted the
7 release of Ca^{2+} ions from their zeolite during ammonium adsorption. Zeolite was also applied for
8 phosphorus removal based on the mechanisms of anion exchange and electrostatic attraction [17–19].
9 Few studies focused on simultaneous removal of N and P by zeolite [20]. Karapınar [21] applied the
10 natural zeolite and dosed calcium ions to remove N and P in separated processes.

11 This study for the first time applied natural zeolite only to simultaneously remove
12 orthophosphate and ammonium-nitrogen from high-strength synthetic wastewater and fermentation
13 effluent. Batch and column tests were adopted to confirm the feasibility of using natural zeolite as a
14 pretreatment unit for making fermentation liquor applicable to subsequent processes such as the
15 BNR process. Experimental conditions with sufficient N and P removals were identified. Based on
16 experimental findings, the mechanisms of phosphorus removal by zeolite with the assistance of
17 ammonium were disclosed.

18

19 **2. Materials and methods**

20 **2.1. Materials**

21 The zeolite used in this study was obtained from Shenshi Mine located in Jinyun, Zhejiang
22 Province, China without modification. After crushing, size sieving to 0.8–1.43 mm, washing with
23 deionized water and air-drying at $105 \pm 1 \text{ }^\circ\text{C}$ for 12h, the prepared zeolite was used in the experiments.
24 The chemical and physical characteristics of the zeolite were reported in Lin *et al.* [16]. In brief, the
25 natural zeolite has main mineral species of clinoptilolite-Na, heulandite and quartz, with surface area

1 of 14.33 m² g⁻¹ and an ion exchange capacity (IEC) of 0.92 meq g⁻¹.

2 The feed solutions (N-P mixtures) were prepared by mixing and diluting 4000 mg-N l⁻¹ of
3 ammonium chloride (NH₄Cl) and 1000 mg-P l⁻¹ of sodium di-hydrogen phosphate (NaH₂PO₄) stock
4 solutions at prescribed ratio. The pH of feed solution was adjusted by adding 0.5 M of sodium
5 hydroxide (NaOH) or hydrochloric acid (HCl). All chemicals were of analytical grade. Wastewater
6 was collected from the effluent of the laboratory fermentation reactor of swine manure at pH 9.3 and
7 35 °C. The fermentation effluent had 1.11% of total solids (TS), 63.1 mg l⁻¹ of orthophosphate
8 phosphorus (PO₄⁻-P), 1252 mg l⁻¹ of ammonium nitrogen (NH₄⁺-N), 5470 mg l⁻¹ of volatile fatty
9 acids (VFAs) and 2804 mg-CaCO₃ l⁻¹ of total alkalinity.

10

11 **2.2. Batch experiments**

12 The batch experiments in 250 ml conical flasks were conducted to consider the effects of pH,
13 ammonium and phosphate concentrations on adsorption/removal performances. The flasks with 100
14 ml solution and 10 g natural zeolite were capped and shaken horizontally at 150 rpm and 25 °C for
15 24 h in a thermostatic shaker (HZQ-X3000, China). **Table S1** lists the experimental conditions. The
16 suspension was filtered via 0.45 µm filter and the filtrate was analyzed. After tests, the zeolites and
17 precipitate at the flask bottom were collected and washed by deionized water and then freeze-dried
18 (SCIENTZ-12N, China) for 24h. All the above procedures were repeated at least in triplicates with
19 the mean values being reported.

20

21 **2.3. Column experiments**

22 The fixed-bed column experiments were carried out in vertical upflow columns (made of
23 Plexiglas) with 1 m height and 60 mm internal diameter at room temperature (20±1 °C). The column
24 was filled with 300g of the natural zeolite at 23 cm depth. The influent with desired pH were pumped
25 into the column bottom using the metering pump (MasterFlex L/S, Cole Parmer, USA) at a constant

1 flow rate of 10mlmin^{-1} , giving 20 min of contact time. **Table S1** lists the other experimental
2 conditions. Effluent from the column was collected and filtered via $0.45\ \mu\text{m}$ filter for analysis.

3

4 **2.4. Analytical methods**

5 Determination of TS, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$ and total alkalinity (titrated to pH 4.3) in filtrate were in
6 accordance with the Standard Methods [22]. pH of suspension was measured using a pH meter
7 (Multi 340i-WTW, Germany). Concentrations of Ca^{2+} and K^+ were measured using atomic
8 absorption spectroscopy (Hitachi-Z 5000, Japan). The concentrations of VFAs (C_2 to C_5) were
9 determined using a gas chromatography (7890A, Agilent, USA) fitted with HP-FFAP (30 m \times 0.25
10 mm \times 0.25 mm) capillary column and FID detection. The surface morphology and chemical
11 compositions of zeolite and collected precipitates were analyzed by the same methods used in Lin *et*
12 *al.* [16].

13 The removal performance was evaluated by the amount of ammonium or phosphate removed by
14 per unit mass of zeolite, which could be calculated according to $q = V (C_0 - C_e) / M$, where q is the
15 removal capacity (mg g^{-1}), C_0 and C_e are the initial and equilibrium concentrations of nitrogen or
16 phosphorus (mg l^{-1}), respectively, V is the feed solution volume (l) and M is the mass of zeolite
17 used (g).

18

19 **3. Results**

20 **3.1. Batch tests**

21 In P-only tests, $100\ \text{mg-P l}^{-1}$ was effectively removed at pH 8–11, reaching 60.2% removal
22 ($0.607\ \text{mg g}^{-1}$) at pH 11 (**Fig. 1**). Conversely, P removal at pH $<$ 7 was low. Similar or contradictory
23 results about the pH-dependent phosphorus removal by zeolites were listed in **Table 1**. Different
24 chemical compositions of zeolites may be responsible to the noted difference in pH dependence. In
25 N-P mixtures, the ammonium adsorption capacity onto the tested zeolite used was declined with

1 increasing pH at alkaline condition, especially at pH>9. This observation correlates with the findings
2 by Lin *et al.* [16]. The P removal was improved in the presence of ammonium, particularly significant
3 at pH 9–11 (**Fig. 1**). Restated, the P removal rate at pH 9, 10 and 11 was increased from 41.2%, 46.0%
4 and 60.2% to 85.8%, 99.7% and 100%, respectively in the presence of 1000 mg l⁻¹ ammonium. White
5 precipitates were noted to form during the test. Hence, as **Fig. 1** shows, pH>9.0 had adverse effects
6 on ammonium removal but enhanced phosphate removal. At pH 9.3, high removals of both P and N
7 were achieved.

8 Further tests at pH 9.3 were conducted with 100 mg-P l⁻¹ and 0–2000 mg-N l⁻¹ or 1000 mg-N l⁻¹
9 and 0–1000 mg-P l⁻¹ (**Fig. 2**). With initial 100 mg-P l⁻¹, the P removal was increased from 43.8% to
10 98.9% as N was increased to 200 mg l⁻¹ (**Fig. 2a**). With up to 200 mg-N l⁻¹, all dosed ammonium was
11 removed by the zeolite. As the N concentration was further increased, the P removal rate was
12 remained at around 100%, but the N removal rate was declined, reaching 48% at 2000 mg-N l⁻¹ (**Fig.**
13 **2a**). With 1000 mg-N l⁻¹, the removal of dosed 20–400 mg-P l⁻¹ was complete; however, the P
14 removal rate declined at >600 mg-P l⁻¹ (**Fig. 2b**). The P removal was 54.2% when using the mixture
15 of 1000 mg-N l⁻¹ + 1000 mg-P l⁻¹ (**Fig. 2b**). In all the tests in **Fig. 2b**, the N removal rate was kept
16 around 70% regardless of the P concentration.

17 As noted in the above tests, the tested zeolite removed limited quantities of dosed P, reaching
18 0.607 mg g⁻¹ at pH 11. At pH 9.3, the N removal depended only on N concentration rather than on P
19 concentration. The adsorption isotherm at 25 °C resembled a Langmuir curve with an abrupt increase
20 in adsorption quantity at low N concentration regime (**Fig. S1**). Conversely, the P removal was
21 significantly affected by the N concentration.

22 Ammonium removal by zeolite was proposed as monolayer molecular adsorption with zeolite
23 [13,23]. Rate-limiting step for P removal with zeolite was claimed as the electron exchange between
24 phosphorus and the zeolite surface [19]. In the N-P mixture both ammonium and phosphate were
25 mostly removed in 3 hr. (**Fig 3(a)**). Both kinetic data of N and P removals well fitted the

1 intra-particle diffusion model with three-linear regions (**Fig. 3(b)**) [4,24] using

$$2 \quad q_t = k_d t^{1/2} + C \quad (1)$$

3 where k_d is the coefficient of intra-particle diffusion ($\text{mg g}^{-1} \cdot \text{min}^{-1/2}$). Multi-linear plots indicated that
4 three steps took place in N and P removal processes: firstly, NH_4^+ and PO_4^{3-} diffused from the
5 solution to the external surface of adsorbent; the second step was gradual adsorption stage on the
6 external and internal surface of zeolite, which was followed by the final equilibrium stage. The
7 best-fit results were given in **Table 2**. The k_{d2} and k_{d3} values for P were both much lower than those
8 for N, suggesting that adsorption phase of P was very poor in the present zeolite [24], and PO_4^{3-}
9 removal occurred most probably in the external boundary layer film of liquor surrounding the zeolite
10 particles.

11

12 **3.2. Column tests**

13 The zeolite column was used to treat the synthetic wastewater with 1163 mg-N l^{-1} and 70 mg-P
14 l^{-1} at pH 9.30. At the initial 80 min, both N and P were completely removed. Breakthrough occurred
15 at 100 min. Effluent N concentration reached 50% of the influent at 160 min, while the P
16 concentration was increased slowly, reaching 20 mg-P l^{-1} at 360 min (**Fig. 4a**). Since the contact time
17 was only 20 min, a worse performance for continuous tests was expected compared with the batch
18 tests lasting for 24 h.

19 The result by using the zeolite column to treat real wastewater at 20 min of contact time was
20 shown in **Fig. 4b**. With feeding solution of 63.1 mg-P l^{-1} , 1252 mg-N l^{-1} , $2000 \text{ mg-CaCO}_3 \text{ l}^{-1}$, and
21 $5470 \text{ mg-VFA l}^{-1}$, in the first 60 min of column test, all N and >90% of P were removed with
22 unchanged VFA and TA levels. Breakthrough of N and P occurred since 80 min. Meanwhile, the TA
23 level was gradually increased. At 360 min, the TA in effluent was increased from 2000 mg to 2800
24 mg l^{-1} . The tested zeolite had no adsorption on the VFAs in the suspensions.

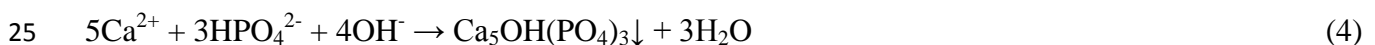
25

1 4. Discussion

2 4.1. Removal mechanisms

3 Soluble inorganic P can be present in four different chemical forms: H_3PO_4 at $\text{pH}<2$; H_2PO_4^- at
4 $\text{pH } 3\text{--}6.5$; HPO_4^{2-} at $\text{pH } 7.5\text{--}12$; PO_4^{3-} at $\text{pH}>12$ [25]. As listed in **Table 1**, different zeolites can
5 have very different P removal capacities, likely due to distinct dominant mechanisms. The increased
6 removal rates of P at high pH in **Fig. 1** suggested that neither anion exchange nor electrostatic
7 attraction control the present P removal since excess OH^- at pH 11 did not compete with HPO_4^{2-} from
8 adsorption sites [26].

9 The SEM images revealed that after wastewater treatment the surface of zeolite was converted
10 from flat and smooth to irregular and rough, with precipitate forming on the surface (**Figs. S2 in the**
11 **Supplementary Materials**). The EDS results revealed that the precipitate had a composition of O
12 (55.8%), Ca (25.5%), P (15.3%), Mg (2.73%), Na (0.67%) and K (0.02%), indicating the precipitate
13 is calcium phosphate precipitate, correlating with the chemical precipitation works reported by Kõiv
14 *et al.*[27]. Based on the previous EDS analysis [16], Ca is the secondary primary cation component
15 (next to Al) in the crystal framework of natural zeolite amounting for 2.09% of total atoms weight,
16 which could be replaced by Na^+ and NH_4^+ in the solution easily [12,28]. Just as shown in Table 3, at
17 initial pH 4.0 condition the co-presence of ammonium promoted 530.7 mg l^{-1} of more Ca^{2+} to release,
18 while at initial pH 9.0 condition, concentrations of both Ca^{2+} and PO_4^{3-} decreased significantly. That
19 was probably because at alkaline condition, Ca^{2+} , OH^- and PO_4^{3-} (in the form of HPO_4^{2-}) could react
20 chemically to form hydroxyapatite (HAP) which has the highest thermodynamic stability among
21 various calcium phosphate precipitates [29]. The following mechanisms were supposed to occur in
22 the present N-P-zeolite system:



1 Restated, the Ca^{2+} on zeolite was exchanged with sodium and ammonium ions in the studied system.
2 Reactions (2) and (3) are independent of the concentration of phosphorus (**Fig. 2b**). Phosphorus was
3 removed by precipitation with the freed Ca^{2+} . In the P-only tests, limited quantities of Ca^{2+} were
4 released by the Na^+ , so limited quantities of phosphorus was removed (**Fig. 2a**). The reaction eq. (4)
5 can occur at $\text{pH}>7$, and will be at favorable rate only at $\text{pH}>9$ [30], which interprets that the excess
6 removal of P at $\text{pH}>9$ (**Fig. 2**) is a kinetics-controlled rather than a thermodynamics-controlled
7 process.

8

9 **4.2. Implications to practice**

10 Comparing the results from column tests with synthetic wastewater and fermentation effluent,
11 the studied zeolite removed 15.6% and 39.4% less ammonium and phosphate, respectively. This
12 occurrence should be attributable to the role of competing ions on adsorption sites for N removal and
13 on precipitation species for P removal.

14 Based on the stoichiometric relationship in Eqs. (3) and (4), to remove 1 mole of P needs 3.3
15 moles of N. At pH 9.3 about 700 mg l^{-1} of ammonium ion ($=50 \text{ mmol l}^{-1}$) were removed by 10 g of
16 the studied zeolite (**Fig. 2a**), while the Ca^{2+} concentrations in the suspensions were noted at 462 mg
17 l^{-1} . Hence, at pH 9.3 if assuming 25 mmol l^{-1} of Ca^{2+} was released accompanied with the adsorption
18 of 50 mmol l^{-1} ammonium ions, considering the corresponding removal of P to be 78.1 mg l^{-1} ($=2.52$
19 mmol l^{-1}), yielding a molar ratio of $(\text{NH}_4^+ \text{ assumption})/(\text{P removal})=(20/1)$, about six times to that by
20 stoichiometry (3/3/1). The Ca^{2+} ions can form precipitates with carbonate and other anions, which
21 account for the excess ammonium adsorption noted in these tests.

22 As K^+ is preferred than NH_4^+ in ion exchange for natural zeolite[31], the 797 mg l^{-1} of K in the
23 fermentation liquor should significantly inhibit ammonium adsorption by zeolite. On the other hand,
24 alkalinity was produced in fermentation [32], with the formed CO_3^{2-} being a strong competitor to
25 phosphate for precipitation[30].Therefore, the N+P wastewaters with few competing cations such as

1 K^+ or Na^+ for ion exchange reaction and competing anions such as CO_3^{2-} for precipitation reaction
2 can reach simultaneous N and P removal by zeolite treatment. When N+P feed has high levels of K^+
3 or Na^+ , high P removal should be achieved with poor N removal performance. With N+P feed of
4 high levels of CO_3^{2-} , P removal would be suppressed. Manipulation of the removal performances of
5 N, P and other ions can be easily made by adjusting the dose amount of zeolite.

6 The studied zeolite did not adsorb VFA, so the produced effluent with low concentrations of N
7 and P can be utilized as supplemented carbon sources for BNR treatment process [5,33]. The
8 adsorbed zeolite and precipitate are enriched in N and P hence can be used as agricultural fertilizers.
9 The zeolite treatment is environmental friendly and cost effective for simultaneous removal of N and
10 P from wastewaters.

11

12 **5. Conclusions**

13 This study applied natural zeolite for simultaneous removal of P and N from wastewaters. At pH
14 9.3, recoveries of P and N were high. A two-step mechanism was proposed to interpret the
15 experimental data: ammonium was adsorbed to zeolite by releasing Ca^{2+} ion to solution, then the
16 released Ca^{2+} ions formed precipitate with phosphate for removal. To reach high levels of
17 simultaneous removal of P and N, an N/P ratio >3.3 was proposed as the criterion. Fermentation
18 liquor after zeolite treatment can provide carbon sources to BNR process and the used zeolite can be
19 used as green fertilizer.

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7

1 **FIGURE CAPTIONS**

2

3 Figure 1. Effects of pH on ammonium and phosphate removal rates by the natural zeolite in P-only
4 and N-P mix, respectively.

5

6 Figure 2(a). Effects of initial ammonium concentration on ammonium and phosphate removal rates
7 by the natural zeolite at initial 100 mg-P l⁻¹ condition.

8

9 Figure 2(b). Effects of initial phosphate concentration on ammonium and phosphate removal rates by
10 the natural zeolite at initial 1000 mg-N l⁻¹ condition.

11

12 Figure 3(a). Effects of contact time on ammonium and phosphate concentration by the natural zeolite
13 at initial 1000 mg-N l⁻¹ and 100 mg-P l⁻¹ condition.

14

15 Figure 3(b). Kinetic plots of intra-particle diffusion model for ammonium and phosphate removals
16 by the natural zeolite at initial 1000 mg-N l⁻¹ and 100 mg-P l⁻¹ condition.

17

18 Figure 4(a). Breakthrough of ammonium and phosphate removals by the natural zeolite in column
19 tests treating N-P mix.

20

21 Figure 4(b). Breakthrough of ammonium, phosphate, total alkalinity and VFAs removals by the
22 natural zeolite in column tests treating the fermentation liquor.

23

Table 1. Zeolites used as the adsorbents for phosphate removal.

Material	$q_t(\text{mgg}^{-1})$	pH	Effect	Removal mechanism proposed	Reference
HDTA-Br modified zeolite	0.194	4.2, 10.4	pH increased, removal increased	Anion exchange & electrostatic attraction	[18]
Zeolite	0.71	3.0–10.0	pH increased, removal decreased	Electrostatic attraction	[26]
HUD synthetic zeolite	79.40	2.5–10.0	pH increased, removal decreased	Chemical interaction & electrostatic attraction	[24]
La/Al-modified zeolite	2.43	2.0–12.0	Favorable range: 4.0-8.0	Electrostatic attraction	[34]
Synthesized zeolite-Al	54.17	5.71	NA	Chemical interaction& ligand exchange.	[20]
Synthesized zeolite-Ca	30.46	6.78	NA	Chemical interaction	[20]
Zeolite	0.30	NA	NA	Electrostatic attraction or anion-exchange.	[19]

Table 2. Kinetic parameters for ammonium and phosphate removal using the natural zeolite.

Adsorption stage	Parameters	NH ₄ -N	PO ₄ -P
First stage	k_{d1}	1.331	0.144
	R^2	0.903	0.990
Second stage	k_{d2}	0.496	0.034
	R^2	0.968	0.949
Third stage	k_{d3}	0.023	7.217×10^{-5}
	R^2	0.877	0.640

Table 3. Concentrations of ions in batch experiments before and after zeolite adsorption.

Solution type	Initial pH	Before/after adsorption	Ion concentration (mg l ⁻¹)					
			NH ₄ ⁺ -N	PO ₄ ³⁻ -P	Ca ²⁺	Na ⁺	Mg ²⁺	K ⁺
P	4.0	before	0	101	0	90.0	0	0
		after	0	94.4	65.3	43.6	1.3	3.1
	9.0	before	0	102	0	123	0	0
		after	0	59.8	2.3	11.2	0.3	0.2
N-P mixture	4.0	before	990	102	0	75.4	0	0
		after	285	92.6	597	545	7.1	58.6
	9.0	before	981	102	0	234	0	0
		after	281	14.5	462	662	7.3	64.5

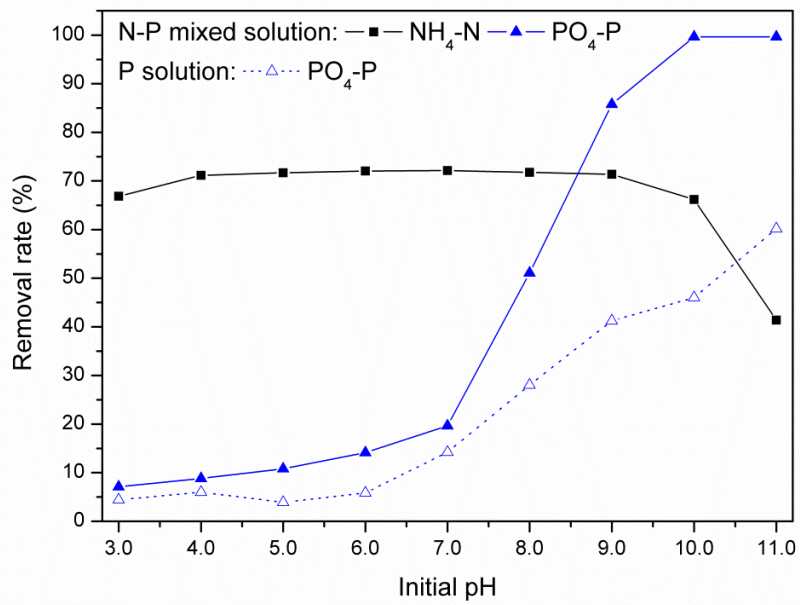


Figure 1. Effects of pH on ammonium and phosphate removal rates by the natural zeolite in P-only and N-P mix, respectively.

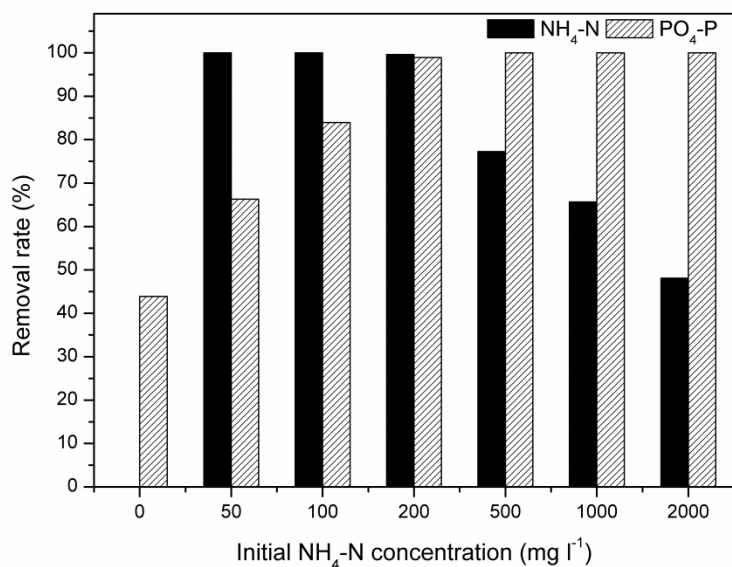


Figure 2(a). Effects of initial ammonium concentration on ammonium and phosphate removal rates by the natural zeolite at initial 100 mg-P l⁻¹ condition.

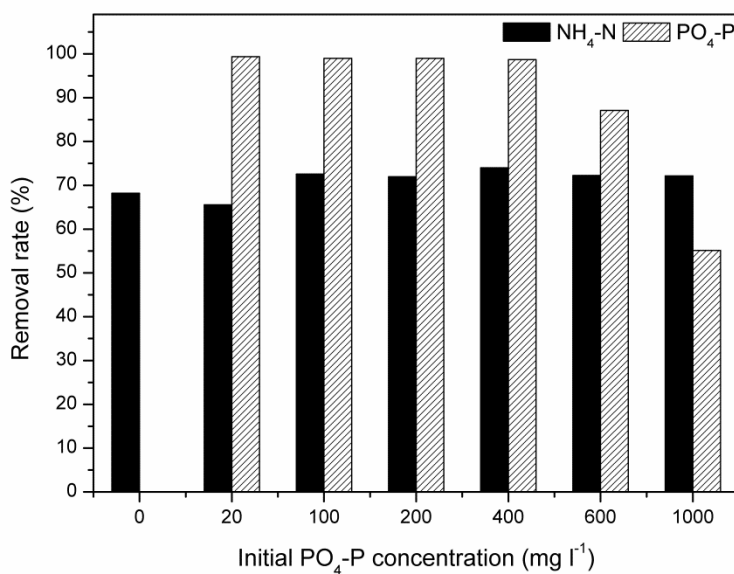


Figure 2(b). Effects of initial phosphate concentration on ammonium and phosphate removal rates by the natural zeolite at initial 1000 mg-N l⁻¹ condition.

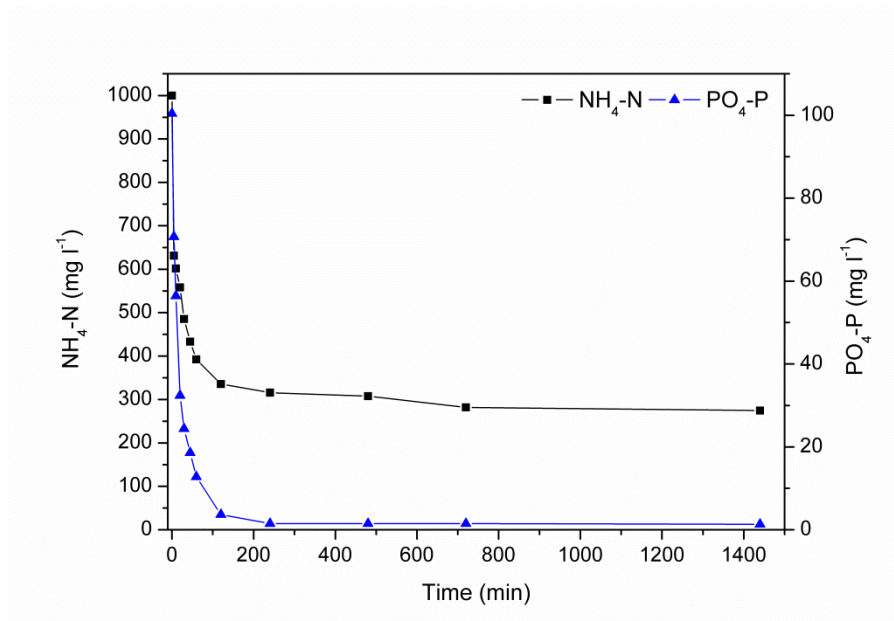


Figure 3(a). Effects of contact time on ammonium and phosphate concentration by the natural zeolite at initial 1000 mg-N l⁻¹ and 100 mg-P l⁻¹ condition.

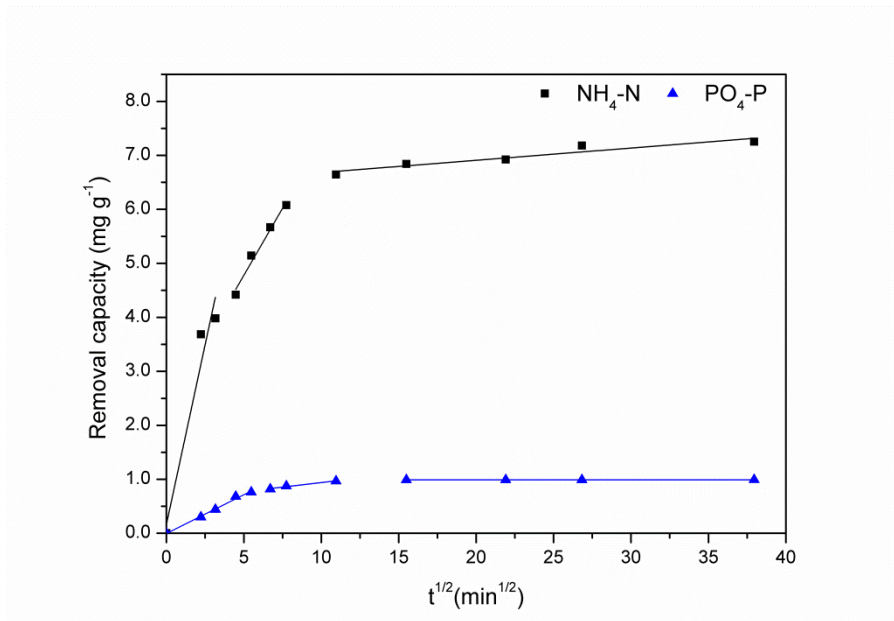


Figure 3(b). Kinetic plots of intra-particle diffusion model for ammonium and phosphate removals by the natural zeolite at initial 1000 mg-N l⁻¹ and 100 mg-P l⁻¹ condition.

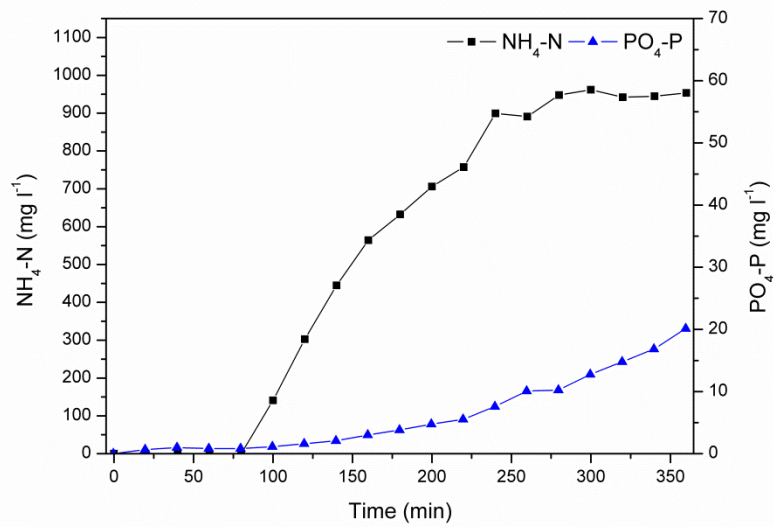


Figure 4(a). Breakthrough of ammonium and phosphate removals by the natural zeolite in column tests treating N-P mix.

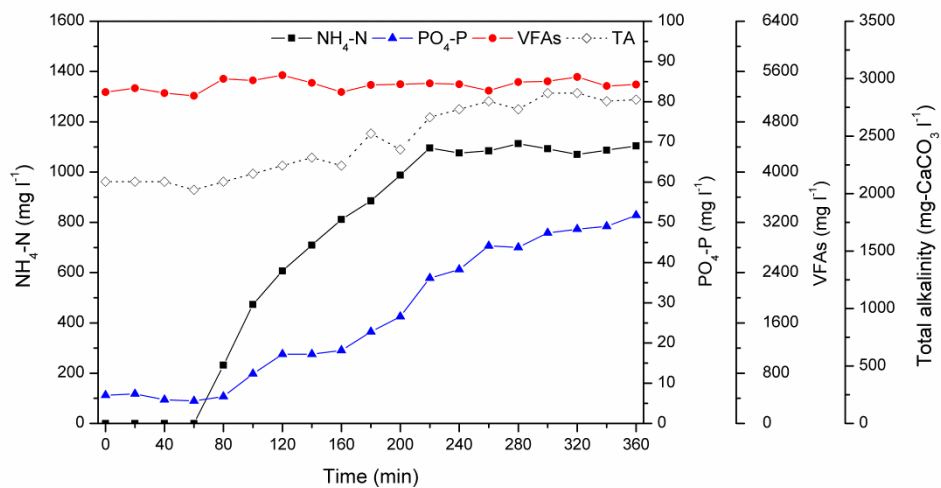


Figure 4(b). Breakthrough of ammonium, phosphate, total alkalinity and VFAs removals by the natural zeolite in column tests treating the fermentation liquor.

SUPPLEMENTARY MATERIALS

Ammonium assists orthophosphate removal from high-strength wastewaters by natural zeolite

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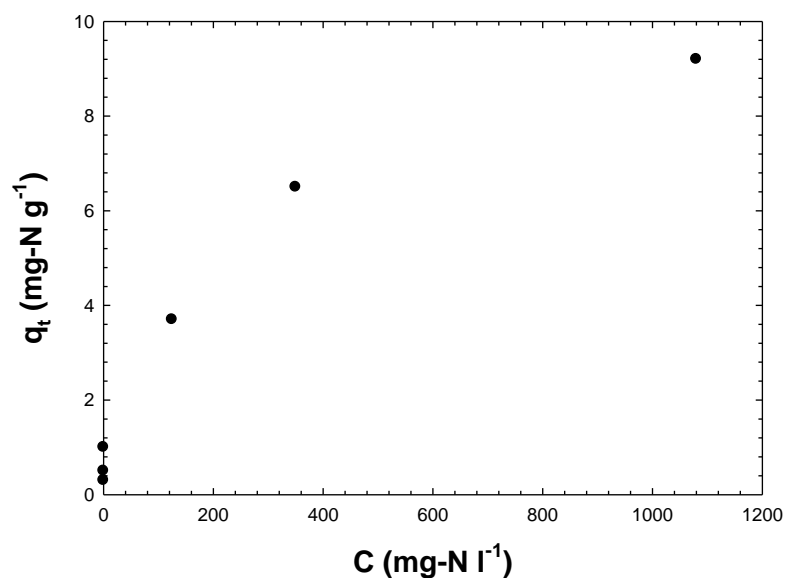
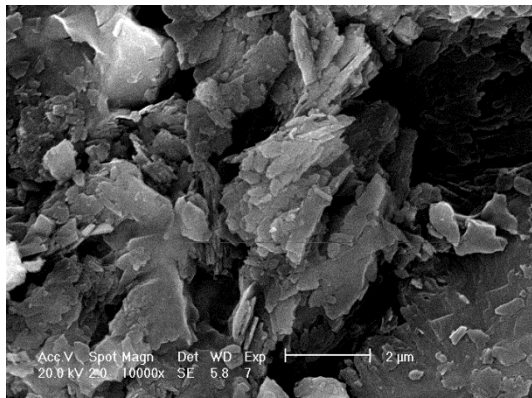
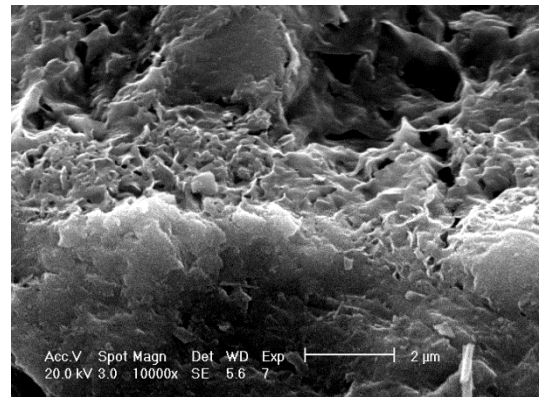


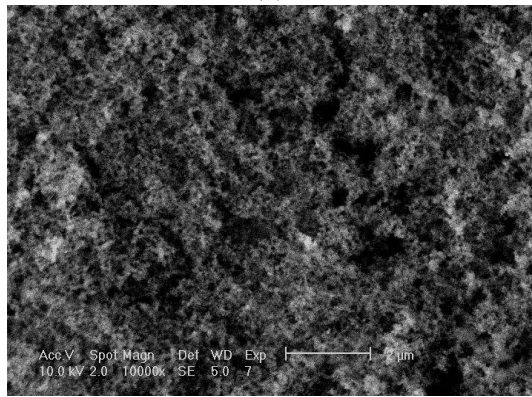
Figure S1. Adsorption isotherm (mg g⁻¹ versus mg l⁻¹) of ammonium ions onto zeolite surface (25°C).



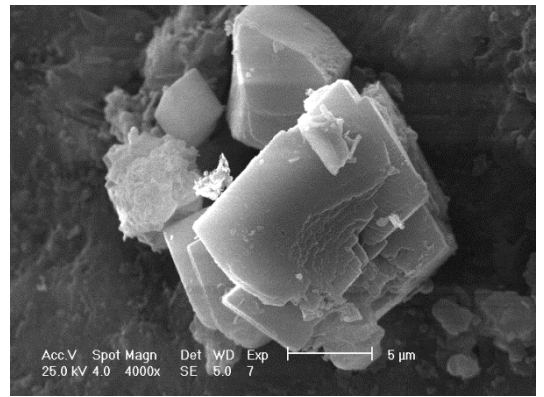
(a)



(b)



(c)



(d)

Figure S2. SEM images of the natural zeolite before adsorption (a), zeolites after treating the N-P feed solution (b), the precipitate formed in feed solution after zeolite treatment (c), and zeolites after treating the fermentation liquor (d).

Table S1. Testing conditions for the batch and continuous experiments.

Factor		Operational conditions					
		Influent type	Initial NH ₄ -N(mgl ⁻¹)	Initial PO ₄ -P(mgl ⁻¹)	pH	Temperature(°C)	Time(h)
Batch	pH	P solution*	0	100	3.0–11.0	25	24
		N-P mixed solution ^b	1000	100	3.0–11.0	25	24
	N-P interaction	N-P mixed solution	0–2000	100	9.3	25	24
		N-P mixed solution	1000	0–1000	9.3	25	24
		N-P mixed solution	1000	100	9.3	25	0–24
Contact time	N-P mixed solution	1000	100	9.3	25	0–24	
Column	Feed	N-P mixed solution	1163	70.4	9.3	20	6
		Fermentation liquor	1252	63.1	9.3	20	6

* Through diluting 1000 mg-P l⁻¹ of sodium di-hydrogen phosphate (NaH₂PO₄) stock solutions with deionized water