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Nitrogen removal enhanced by intermittent operation in a subsurface wastewater infiltration system

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Abstract

A pilot subsurface wastewater infiltration system filled with a mixed soil of red clay + 25% cinder was constructed in a village located in Dianchi valley in south west China to treat rural sewage. At first, the system was continuously fed with rural sewage at a hydraulic loading of $2\,\mathrm{cm\,d^{-1}}$ for over 4 months. The removal of COD, T-P, NH_4^+-N, and T-N over the operation period was achieved at average rates of 82.7, 98.0, 70.0, and 77.7%, respectively. Compared to T-P removal, the lower nitrogen removal rates were attributed to reductive soil condition in the system, which was unfavorable for the nitrification process. An intermittent operation was adopted to improve nitrogen removal. The same performances of COD and T-P removal were achieved in the intermittent operation mode. NH_4^+-N removal was increased from 70% in the continuous feeding mode to over 90%, and T-N removal rate was elevated over 80% even with the average hydraulic loading as high as $8\,\mathrm{cm\,d^{-1}}$. Nitrogen balance calculation suggested that nitrification–denitrification was the main mechanism of nitrogen removal that eliminated 57–76% of the fed T-N. Soil redox potential measurement showed that the oxidative environment was increased through intermittent operation, encouraging nitrification. Correspondingly, soil nitrification potential was increased from less than $0.8\,\mathrm{mg\text{-}N\,kg^{-1}\,h^{-1}}$ in the continuous feeding mode to about $1.6\,\mathrm{mg\text{-}N\,kg^{-1}\,h^{-1}}$ in the intermittent operation mode.

Keywords: Intermittent operation; Nitrogen removal; Redox potential; Subsurface wastewater infiltration system

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1. Introduction

Dianchi, the largest lake in southwest China, has been severely polluted in recent years due to excessive discharge of nitrogen and phosphorus nutrients resulting from population growth and economic development. Total nitrogen (T-N) and total phosphorous (T-P) concentrations of the water in Dianchi lake were about 2.20 and $0.21\,\mathrm{mg\,l^{-1}}$, respectively, in 2002 (Li and Peng, 2003), indicating a serious eutrophication status. Domestic wastewater discharged from decentralized rural areas around Dianchi is one of the main reasons

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for Dianchi's eutrophication (Liu, 2001). Therefore, removal of nitrogen and phosphorus from rural sewage is important to prevent the eutrophication of Dianchi Lake.

A subsurface wastewater infiltration system is a process suitable for domestic wastewater treatment in rural areas. It is an effective way to treat wastewater according to integrated mechanisms of chemical, physical and biological reactions if the infiltration system is carefully designed and managed. Compared to the conventional activated sludge process, this system has many advantages including excellent performance of nitrogen and phosphorus removal, lower construction and operation costs, and easy maintenance (Pell and Nyberg, 1989; Yamaguchi et al., 1996; Sun and He, 1998; Yang and Tian, 1999).

Much research has been carried out to study nitrogen removal performance in the subsurface wastewater infiltration system. The nitrogen removal rate varies from 10 to 90% according to wastewater composition, environmental conditions and operating conditions (Rice and Bouwer, 1984; Lance, 1986; Pell and Nyberg, 1989; USEPA, 1992; Yamaguchi et al., 1996; Sun and He, 1998; Yang and Tian, 1999). Lance (1986) reported that nitrification and denitrification were the main reactions capable of eliminating nitrogen from sewage water in subsurface infiltration systems. In systems filled with loamy soil that were sufficiently aerated, nitrification was encouraged and a carbon source was the restrictive factor to biological nitrogen removal (Lance and Whisler, 1976; Rice and Bouwer, 1984; Schwager and Boller, 1997).

The soil around Dianchi Valley is mostly red clay. Since red clay has low permeability and may lead to an anaerobic condition, which is unfavorable for the nitrification process, nitrogen removal in such soil composed mainly of red clay may be different from the cases mentioned above where soils were loamy.

In the present study, a pilot subsurface infiltration system filled mainly with red clay was constructed in a village located in Dianchi Valley to treat rural sewage. For improving the permeability of red clay, cinder, which is an inorganic waste produced in coal combustion was added into red clay at a weight ratio of 25% (cinder/red clay). Pollutant treatment performances as well as nitrogen removal enhancement by intermittent operation were investigated. Nitrogen removal mechanisms were also analyzed.

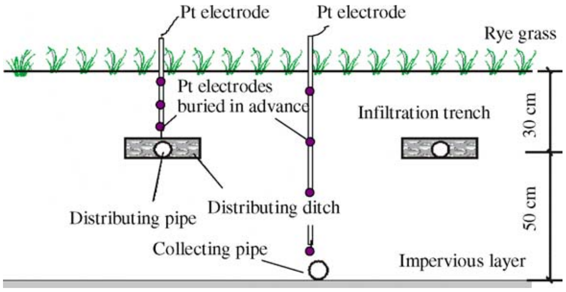

Fig. 1. Schematic diagram of subsurface wastewater infiltration pilot system.

2. Materials and methods

2.1. Pilot system

A 9 m^2 pilot subsurface infiltration system with a length of 3.0 m, width of 3.0 m and depth of 0.8 m was constructed in a village located in the Dianchi Valley (Fig. 1).

The raw rural sewage after sedimentation was pumped into distributing pipes that were installed at the bottom of the infiltration trench. Treated effluent was collected through collecting pipes at the bottom of the pilot system. The surface soil of the infiltration system was seeded with rye grass. The infiltration trench was filled with a mixed soil of red clay combined with cinder at a weight ratio of 25% (cinder/red clay). Cinder is an inorganic waste produced in coal combustion, mainly composed of SiO_2, Al_2O_3 and ferric oxide. The total organic content of the red clay was 0.8%, the pH was 5.7 and the particle size distribution was shown in Table 1.

In the first stage (continuous feeding mode) which lasted for 4.5 months, the system was continuously fed

Table 1
Particle size distribution of red clay

Particle size (mm)	Percentage (%)
>0.25	0.60
0.05–0.25	4.40
0.01–0.05	10.00
0.005–0.01	72.00
0.001–0.005	2.00
<0.001	11.00

with rural sewage at a hydraulic loading of 2 cm d^{-1}. In the second stage (intermittent feeding mode), which lasted for 12.5 months, in order to improve nitrogen removal, an intermittent operation was adopted. Each cycle of the intermittent operation included a flooding period of 24 h and a drying period of 24 h. Average hydraulic loading over one cycle (48 h) was gradually elevated from 2 to 4, 6, 8 and 10 cm d^{-1}. When the average hydraulic loading was increased to 10 cm d^{-1}, soil clogging occurred. The average hydraulic loading was thus decreased to 2 cm d^{-1} again until the pilot test was stopped.

In order to monitor redox potential in the soil in the pilot system, Pt electrodes were buried in the soil in advance at depths of 5, 15 and 25 cm in the infiltration trenches and at 10, 30, 50 and 70 cm between the infiltration trenches (Fig. 1).

2.2. Adsorption test of soil

In order to investigate N and P adsorption capacities of the soil applied in the pilot infiltration system, adsorption batch tests using the mixed soil of red clay + 25% cinder were conducted. As comparison, adsorption testes using pure red clay and loamy soil were also conducted. The former is a typical soil in Dianchi valley and the latter is a type of soil normally adopted in infiltration systems. Soil samples that had been dried at 105 °C for constant weight were put into conical flasks of 250 ml and sterilized at 121 °C and 1.1 MPa for 30 min. A given volume of solutions containing different concentrations of NH_4^+-N, NO_3^--N, NO_2^--N or PO_4^{3-}-P were separately added into each flask. These flasks were shaken at 180 rpm at 25 °C for approximately 24 h. After adsorption equilibrium was achieved, the solution was filtered with a 0.45-μm-membrane filter for analysis. The adsorption capacity of soil for N or P was calculated as follows:

$$q = \frac{(C_0 - C)V}{M} \tag{1}$$

where q is the adsorption capacity of soil (mg g^{-1}), C_0 the initial concentration of the target substance in the mixed soil solution (mg l^{-1}), C the equilibrium concentration of the target substance in the mixed soil solution (mg l^{-1}), V the volume of the solution (l) and M is the dry weight of soil (g).

Table 2
Rural sewage quality after sedimentation (unit: mg l^{-1} except pH)

COD	30–200
T-P	0.5–7.0
PO_4^{3-}-P	0.4–6.5
T-N	10–40
NH_4^+-N	1.9–30
SS	50–150
pH	7–8.5

2.3. Quality of raw sewage

The quality of raw rural sewage used in the study is shown in Table 2. Affected greatly by local rainfall, the sewage concentration fluctuated greatly during the operation period.

2.4. Analysis items and methods

According to standard methods (Chinese EPA, 1997), potassium dichromate method was used for chemical oxygen demand (COD) analysis, colorimetric method was used for NH_4^+-N, NO_3^--N, NO_2^--N, T-N, PO_4^{3-}, and T-P analysis, gravimetric method was used for SS analysis.

Total nitrogen of grass and soil was analyzed by $NaCO_3$ fusion method and total phosphorus of grass and soil was analyzed by Kjeldahl method (Nanjing Soil Research Institute, 1999).

Nitrification potential has often been used to indicate the activity of nitrifying bacteria in soil (Hart, 1994). Soil samples of 20 g taken from the different positions of the infiltration system were put into separate conical flasks of 250 ml. One hundred millilitres substrate solution containing NH_4^+-N was added, and the flasks were shaken at 180 rpm at 25 °C. After a short time of incubation, ammonia nitrogen was oxidized to nitrate nitrogen by nitrifying bacteria. After incubation for 24 h, suspended soil solution was filtered through a 0.45 μ-membrane filter for analysis of NO_3^--N and NO_2^--N. The nitrification potential was calculated as follows:

$$\omega = \frac{N_0 - N_t}{t}\,\frac{V_1 + V_2}{m(1 - w)} \tag{2}$$

where ω is the rate of nitrate nitrogen production by per unit weight of soil sample (mg-N kg^{-1} h^{-1}), N_0 the initial nitrate concentration in the mixed soil solu-

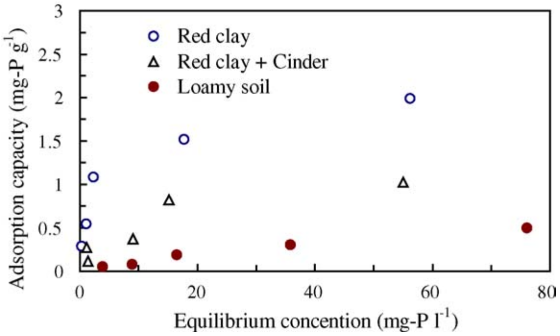

Fig. 2. Phosphorus (PO_4^{3-}-P) adsorption isotherms of different soils at 25 °C.

tion (mg l^{-1}), N_t the nitrate concentration in the mixed soil solution after incubation for time t (mg l^{-1}), V_1 the substrate solution volume (l), V_2 the water volume in the soil sample (l), m the mass of the soil sample (kg) and w is the water content ratio in the soil sample (fraction).

The measurements for one soil sample were replicated more than three times, and the results were averaged.

3. Results and discussion

3.1. Adsorption isotherms of soil

3.1.1. Phosphorus adsorption

The mixed soil of red clay + 25% cinder was tested for investigation of phosphorus adsorption isotherm, which was compared to those of pure red clay and loamy soil (Fig. 2).

The data in Fig. 2 indicated a high phosphorus (PO_4^{3-}-P) adsorption capacity of red clay, which might be due to its fine particles and large specific surface area. In addition, aluminous and ferric compounds contained in red clay can enhance phosphorus adsorption. However, the permeability of red clay is quite low. Its permeability coefficient is lower than 10 cm d^{-1}, while the permeability coefficient of loamy soil, which is a type of soil normally adopted in infiltration systems, is as high as 45.42 cm d^{-1}. To improve red clay's permeability, cinder was added into red clay at a weight ratio of 25% (cinder/red clay) and the mixed soil's permeability coefficient was increased to 35.61 cm d^{-1}. Compared to red clay, the mixed soil's adsorption capacity decreased, but was still higher than that of loamy soil.

Generally, Langmuir's isotherm model is widely used to analyze adsorption characteristics of soil according to the following equation:

$$\frac{C}{q} = \frac{C}{q_{\max}} + \frac{1}{Kq_{\max}} \tag{3}$$

where q is the adsorption capacity of soil (mg-P g^{-1}), $q_{\max}$ the maximum adsorption capacity of soil (mg-P g^{-1}), C the equilibrium concentration of phosphorus in the mixed soil solution (mg-P l^{-1}) and K is the adsorption coefficient (l mg^{-1}).

By applying Eq. (3) to the data shown in Fig. 2, a linear regression analysis of C/q and C was conducted by Microsoft Excel. According to the slope ($1/q_{\max}$) and intercept ($1/(Kq_{\max})$) of the fitted linear regression line, $q_{\max}$ and K were calculated (Table 3).

Assuming that the phosphorus concentration in the influent is 3 mg-P l^{-1}, the density of soil is 1.2 g cm^{-3} and hydraulic loading is 2 cm d^{-1}, the saturation time for phosphorus adsorption of the mixed soil of red clay + 25% cinder was estimated to be about 15 years according to the adsorption parameters shown in Table 3.

3.1.2. Nitrogen adsorption

Adsorption isotherms of the mixed soil of red clay + 25% cinder to NO_3^--N, NO_2^--N and NH_4^+-N ions were investigated (Fig. 3). The mixed soil had little adsorption capacity on NO_3^--N and NO_2^--N. This

Table 3
Regression analysis results of phosphorus and nitrogen adsorption isotherms

Adsorption target	Items	Red clay	Red clay + 25% cinder	Loamy soil
Phosphorus	$q_{\max}$ (mg-P g^{-1})	2.057	1.234	1.091
	K (l mg^{-1})	0.562	0.149	0.0107
Ammonia nitrogen	$q_{\max}$ (mg-N g^{-1})	–	0.506	–
	K (l mg^{-1})	–	0.010	–

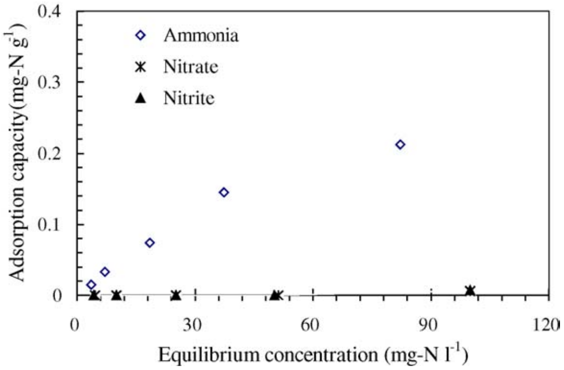

Fig. 3. Nitrogen adsorption isotherms of red clay + 25% cinder at 25 °C.

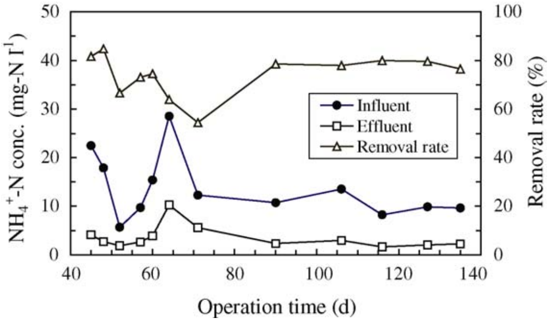

Fig. 4. NH$_4^+$-N removal performance in the continuous feeding mode.

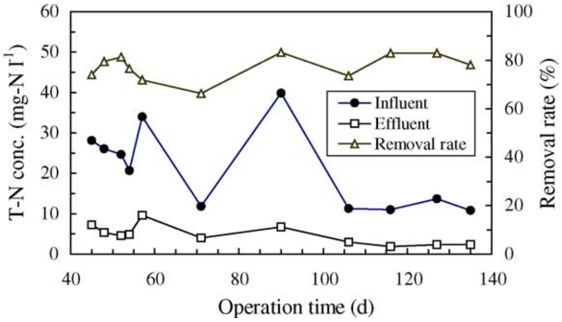

Fig. 5. T-N removal performance in the continuous feeding mode.

might be due to the negative charge of the soil. However, NH$_4^+$-N ions with positive charge were adsorbed easily by the soil.

Similarly, regression analysis was conducted by applying Eq. (3) to the data in Fig. 3 and the results are also shown in Table 3. Assuming that the concentration of ammonia nitrogen in the influent is 10 mg l^{-1}, the saturation time for ammonia nitrogen adsorption was estimated to be about 0.50 years even that the biological reaction on ammonia nitrogen adsorbed in the soil is not taken in consideration. However, it should be emphasized that ammonia nitrogen ions adsorbed in the soil are readily decomposed to nitrate nitrogen by microorganisms and the soil is restored for successive adsorption of ammonia nitrogen.

3.2. Removal performance at the continuous feeding

At the first stage, the pilot system was continuously fed with rural sewage for 4.5 months. Delayed by some problems of the pilot plant, the water quality monitoring was conducted after the 40th day of operation. Water samples were collected twice 1 week in the first 2 months and after that once 2 weeks. Table 4 shows the pollutant removals and their standard deviations of the pilot system over the test period. Profiles of ammonia and T-N removal performance are represented in Figs. 4 and 5, respectively. Over the test period, the average values of the influent pH and temperature were 7.12 and 24.2 °C, and their standard deviations were 0.052 and 2.67, respectively.

Average COD and T-P removal rates as high as 82.7 and 98%, respectively, were achieved. Excellent T-P removal was attributable to the soil's high phosphorus adsorption capacity as shown in Fig. 2.

Table 4
Pollutant removal of the pilot system at continuous feeding mode

Items	COD	T-P	T-N	NH$_4^+$-N
Influent concentration (mg l^{-1})	30–139 (76.0)	0.4–4.2 (1.94)	11.8–40.0 (21.1)	5.7–30.0 (13.2)
Effluent concentration (mg l^{-1})	6–21 (11.7)	0.032–0.085 (0.04)	1.9–10.5 (4.7)	1.8–10.3 (4.0)
Removal rate (%)	71.2–95.5 (82.7)	97.5–99.1 (98.0)	71.9–82.9 (77.7)	66.5–79.9 (70.0)
Standard deviation of removal rates	2.88	2.37	2.66	2.41

Note: Data in parentheses were mean values.

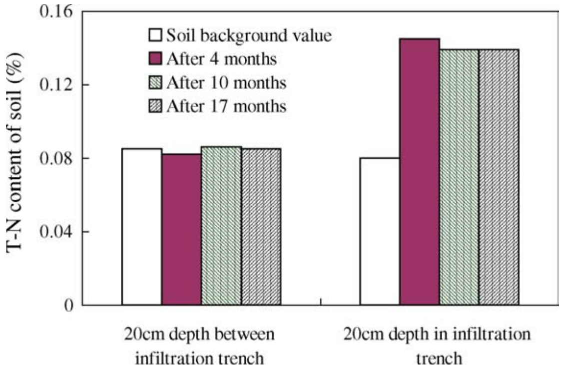

Fig. 6. Soil T-N content changes over the operation period of 17 months.

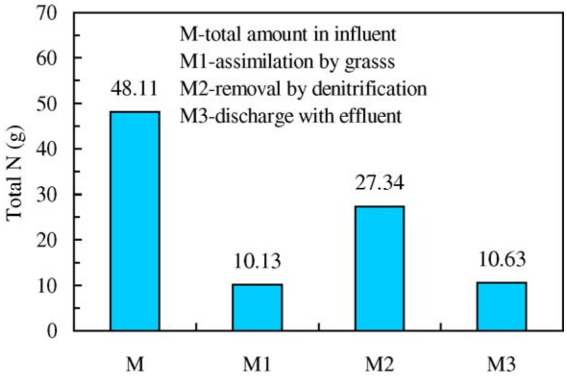

Fig. 7. Nitrogen balance during the continuous feeding mode.

However, NH_4^+-N and T-N removal rates were only around 70 and 77.7%, respectively. The lower NH_4^+-N removal rate was attributable to an insufficient nitrification in the continuous feeding mode, which resulted in a lower T-N removal rate.

Nitrogen removal mechanisms in subsurface infiltration systems include soil fixation, ammonia volatilization, grass uptake and nitrification–denitrification. Volatilization loss of NH_4^+-N can be disregarded since the red clay filled in the pilot system was acidic (pH about 5.7).

An adsorption test indicated that the soil had an adsorption capacity to ammonia nitrogen (Fig. 3). To follow up the behavior of nitrogen adsorbed in soil, the total nitrogen (T-N) contents of soil in the infiltration trench and between the infiltration trenches were periodically measured over the operation period (Fig. 6), which totally lasted for 17 months including the second stage operation (intermittent feeding mode). The results showed that the T-N content of the soil fluctuated little after 4 months of wastewater feeding, which suggested that the adsorption and degradation of ammonia nitrogen in soil was balanced when the infiltration system was stable. Adsorbed ammonia nitrogen was biologically transferred to nitrate nitrogen, which was not easily adsorbed by soil due to the fact that its negative charge was the same with the soil's. The increase of T-N content of the soil in the infiltration trench in the first 4 months was attributed to initial microbial proliferation. Therefore, fixation and accumulation of nitrogen by soil could be disregarded when the infiltration system was stable. Removal mechanisms of nitrogen in the system are mainly attributable to grass uptake and nitrification–denitrification.

Disregarding volatilization and soil fixation, mass balance of nitrogen during the continuous feeding operation was calculated as follows. A harvest cycle (2 weeks) of grass was considered for calculation. The amount of T-N that was assimilated by grass (M_1) was obtained by harvesting all grass growing in the pilot system within the cycle and measuring the weight and T-N content of the harvested grass. As the total amount of nitrogen that entered the pilot system (M) with the influent and the amount that was discharged (M_3) with the effluent in the cycle were available, the nitrogen amount that was removed by nitrification–denitrification (M_2) could be calculated by the following equation:

$$M_2 = M - M_1 - M_3 \tag{4}$$

Calculation results of nitrogen balance in the infiltration system during the continuous feeding are given in Fig. 7.

The data in Fig. 7 indicated that nitrification–denitrification was the primary nitrogen removal path in the subsurface wastewater infiltration system, which eliminated 27.34 g of T-N, accounting for 57% of the fed T-N in one harvest cycle (2 weeks). Grass uptake was another important way in nitrogen removal, accounting for the elimination of about 21% of the fed T-N.

Since the above analysis was carried out in a grass growing period when the grass had a maximum nitrogen assimilation capacity, there was little potential to enhance the nitrogen removal by promoting grass

Table 5
Pollutant removals of the pilot system at intermittent feeding mode

Hydraulic loading (cm d^{-1})	COD removal (%)	T-P removal (%)	T-N removal (%)	$NH_4{}^+$-N removal (%)
2	68.8–95.9 (90.2)	96.2–99.9 (98.3)	87.9–92.9 (91.0)	91.7–99.5 (95.0)
4	87.0–92.5 (87.0)	96.0–99.9 (98.5)	85.3–89.2 (87.1)	93.2–99.9 (95.9)
6	85.8–95.7 (92.4)	97.5–99.8 (98.7)	79.1–89.5 (83.8)	95.3–99.9 (98.2)
8	78.5–88.9 (85.0)	91.5–99.9 (95.6)	78.6–92.8 (85.0)	82.9–98.5 (92.8)
10	58.4–82.3 (71.8)	93.0–99.2 (96.7)	68.9–83.4 (79.1)	68.8–83.4 (82.1)

Note: data in parentheses were mean values.

uptake. The key problem is to improve the total N removal through creation of an environment suitable for the nitrification–denitrification processes.

3.3. Enhancement of T-N removal by intermittent feeding

As discussed in the previous session, $NH_4{}^+$-N and T-N removals in the pilot infiltration system were relatively low at the continuous feeding. In order to improve nitrification as well as nitrogen removal, an intermittent feeding operation was applied to the system in the second stage. Each cycle of the intermittent operation included a flooding period of 24 h and a drying period of 24 h. It was expected that the oxidative condition of the soil could be improved through the drying period of the intermittent operation, which was favorable for the nitrification process. The second stage test was totally lasted for 12.5 months. Average hydraulic loading over one cycle (48 h) was gradually elevated from 2 to 4, 6, 8 and 10 cm d^{-1}. The system was operated for about 1 month at each hydraulic loading. When the average hydraulic loading was elevated to 10 cm d^{-1}, soil clogging occurred. Then the average hydraulic loading was decreased to 2 cm d^{-1} and the system has been operated at such low hydraulic loading for about 7 months until the test was stopped. Only experimental data obtained during five hydraulic loadings of 2–10 cm d^{-1} were represented here. Over the test period, the average values of the influent pH and temperature were 7.51 and 25.1 °C, and their standard deviations were 0.076 and 2.27, respectively.

Table 5 shows the pollutant removals of the pilot system at five different hydraulic loadings at intermittent feeding mode.

The same performance of COD and T-P removal was achieved in the intermittent operation mode. Profiles of $NH_4{}^+$-N and T-N removal in the intermittent operation mode with different average hydraulic loadings are shown in Figs. 8 and 9, respectively.

Although the influent $NH_4{}^+$-N and T-N concentrations fluctuated greatly due to season change in the test field, the operation of the pilot system was quite stable. The $NH_4{}^+$-N removal rate was increased from 70% in the continuous feeding mode to over 90% in the intermittent operation mode, even when the average hydraulic loading was increased to 8 cm d^{-1} (Fig. 8). This showed that nitrification was greatly improved in

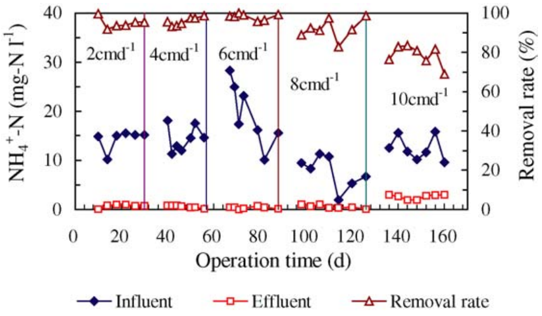

Fig. 8. $NH_4{}^+$-N removal performance in the intermittent feeding mode.

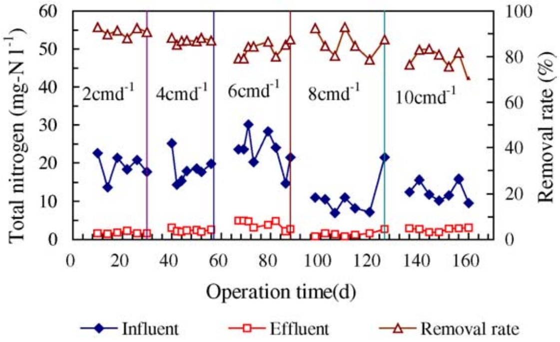

Fig. 9. T-N removal performance in the intermittent feeding mode.

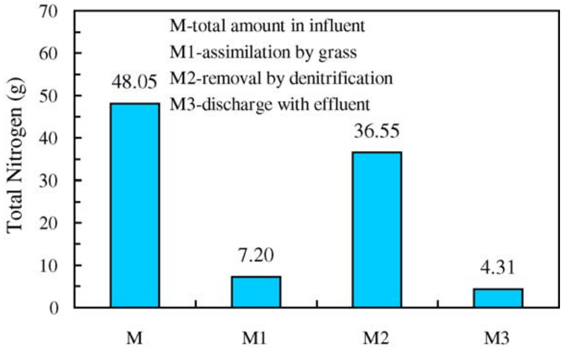

Fig. 10. Nitrogen balance during the intermittent operation mode.

the pilot system in the intermittent operation mode. Correspondingly, the T-N removal rate was increased from 77 to about 90% at an average hydraulic loading of 2 cm d^{-1}. Even when the average hydraulic loading was as high as 8 cm d^{-1}, the T-N removal rate was over 80% (Fig. 9). When the average hydraulic loading was increased to 10 cm d^{-1}, soil clogging occurred due to overfeeding and soil permeability decreased quickly to a very small value. Slight elevation of the effluent NH_4^+-N at this condition was attributed to deterioration of nitrification caused by soil clogging. For improving the soil clogging, the average hydraulic loading was dropped to 2 cm d^{-1} again. In successive 7 months operation, soil clogging gradually disappeared and the permeability was recovered.

Mass balance calculation of nitrogen was also carried out during one harvest cycle (2 weeks) according to Eq. (4) for the intermittent operation mode. The results showed that nitrogen removal through nitrification–denitrification was improved up to 36.55 g of T-N, i.e. 76% of the fed T-N (Fig. 10) in the cycle. This suggested that the intermittent operation could promote nitrification in the pilot system and an increase in the T-N removal rate.

3.4. Redox potential

Soil redox (e_h) has been widely used to indicate soil aeration conditions, and it is an important factor influencing the nitrification–denitrification process (Meek and Grass, 1975). Pt electrodes were installed at different depths both in the infiltration trenches and between the infiltration trenches to investigate soil e_h changes in the pilot system. The results in the continuous feeding mode are shown in Table 6, also drawn in Figs. 11 and 12 by dotted lines. e_h values of soils at all depths were lower than 250 mV and the lowest value was −169 mV near the distribution pipe. This

Table 6
e_h measurement results in the continuous feeding mode

Location of electrode	Depth (cm)	e_h (mV)
In infiltration trenches	5	224
	15	155
	25	−169
Between infiltration trenches	10	180
	30	137
	50	145
	70	52

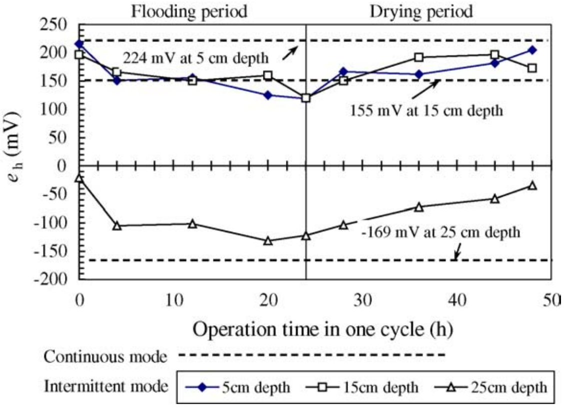

Fig. 11. e_h changes of soil in the infiltration trenches in two operation modes.

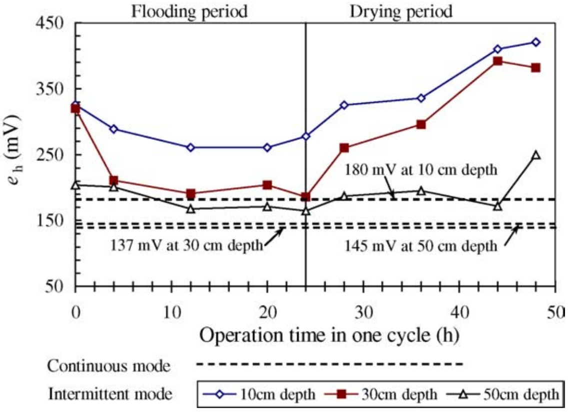

Fig. 12. e_h changes of soil between infiltration trenches in two operation modes.

suggested that in the continuous feeding mode, soil in the pilot system was in a reductive condition where nitrification reaction might be inhibited.

Soil e_h was also measured over the flooding period and drying period in the intermittent operation mode. e_h changes of the soil in the infiltration trenches and between the infiltration trenches are shown in Figs. 11 and 12, respectively.

As for soil e_h changes in the infiltration trench (Fig. 11), a similar tendency was observed for all depth, i.e. soil e_h decreased somewhat in the flooding period but rose slowly in the drying period. For example, the soil e_h at a depth of 25 cm in the infiltration trench near the distributing pipe quickly decreased to below −100 mV in the flooding period due to oxygen consumption mainly caused by organic decomposition by microorganisms, but slowly rose up to a maximum value of −20 mV in the drying period. Compared to soil e_h values in the continuous feeding mode, although e_h at the surface soil (5 cm depth) was not enhanced furthermore in the intermittent feeding mode, e_h values at deeper soil, especially at 25 cm depth in the drying period were obviously elevated.

Soil e_h changes between the infiltration trenches showed a similar tendency to those in the infiltration trenches (Fig. 12). That is, soil e_h decreased somewhat in the flooding period, and then rose in the drying period. Soil e_h values at all depths in the intermittent feeding mode were higher than those at same depths in the continuous feeding mode. Especially in the drying period, the soil e_h at the depths of 10 and 30 cm rose to about 400 mV.

The above soil e_h measurement results suggested that the oxidative condition was enhanced by intermittent feeding mode encouraging nitrification.

3.5. Soil nitrification potential

Results of nitrification potential measurement in the two feeding modes are shown in Fig. 13. In the continuous feeding mode, a soil nitrification potential as high as 0.8 mg-N kg^{-1} h^{-1} was achieved. When the intermittent operation was adopted, the soil nitrification potential was enhanced. The soil at a depth of 15 cm in the infiltration trench (near the distributing pipe) had the greatest nitrification potential of 1.6 mg-N kg^{-1} h^{-1}, which was much higher than that in the continuous feeding mode. The results suggested that the intermittent operation mode was an effective method to promote nitrification. Because the most $NH_4{}^+$-N in sewage was nitrified to nitrite and nitrate in the infiltration trench and the $NH_4{}^+$-N concentration of sewage was decreased to a low level when sewage flowed into soil between infiltration trenches, the amounts and activities of soil nitrifying bacteria between infiltration trenches were much lower than those in filtration trench.

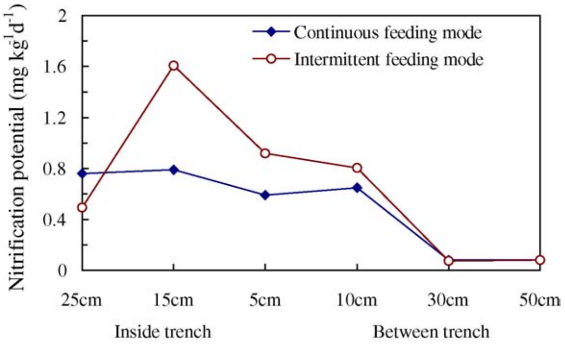

Fig. 13. Nitrification potential of soil in the pilot infiltration system.

4. Conclusions

In the continuous feeding mode, average rates of COD, T-P, $NH_4{}^+$-N and T-N removal were 82.7, 98, 70 and 77.7%, respectively, in the subsurface wastewater infiltration pilot system filled with the mixed soil of red clay + 25% cinder at a hydraulic loading of 2 cm d^{-1}. The low T-N removal rate was attributed to insufficient nitrification.

An intermittent operation including a flooding period of 24 h and a drying period of 24 h was adopted to improve nitrogen removal. The same COD and T-P removal rates were achieved in the intermittent operation mode. The $NH_4{}^+$-N removal rate was elevated from 70% in the continuous feeding mode to over 90% in the intermittent operation mode, and the T-N removal rate was over 80%, even with the hydraulic loading as high as 8 cm d^{-1}.

Nitrogen balance calculation suggested that nitrification–denitrification was the main mechanism of nitrogen elimination, which accounted for 57–76% of the fed T-N. Soil redox potential measurements showed that the oxidative environment was enhanced through the intermittent operation, which encouraging nitrification. Soil nitrification potential was increased from less than 0.8 mg-N kg^{-1} h^{-1} in the continuous feeding mode to about 1.6 mg-N kg^{-1} h^{-1} in the intermittent operation mode.

The above results provided an effective way to enforce nitrogen removal in subsurface infiltration system filled mainly with red clay with a low permeability.

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