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Study on nitrogen removal enhanced by shunt distributing wastewater in a constructed subsurface infiltration system under intermittent operation mode

Yinghua Li, Haibo Li*, Tieheng Sun, Xin Wang

Key Laboratory of Regional Environment and Eco-Remediation, Ministry of Education, Shenyang University, Shenyang 110044, China

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ABSTRACT

Subsurface wastewater infiltration system is an efficient and economic technology in treating small scattered sewage. The removal rates are generally satisfactory in terms of COD, BOD_5, TP and SS removal; while nitrogen removal is deficient in most of the present operating SWIS due to the different requirements for the presence of oxygen for nitrification and denitrification processes. To study the enhanced nitrogen removal technologies, two pilot subsurface wastewater infiltration systems were constructed in a village in Shenyang, China. The filled matrix was a mixture of 5% activated sludge, 65% brown soil and 30% coal slag in volume ratio for both systems. Intermittent operation mode was applied in to supply sufficient oxygen to accomplish the nitrification; meanwhile sewage was supplemented as the carbon source to the lower part in to denitrify. The constructed subsurface wastewater infiltration systems worked successfully under wetting-drying ratio of 1:1 with hydraulic loading of $0.081\,m^3/(m^2\,d)$ for over 4 months. Carbon source was supplemented with shunt ratio of 1:1 and shunt position at the depth of 0.5 m. The experimental results showed that intermittent operation mode and carbon source supplementation could significantly enhance the nitrogen removal efficiency with little influence on COD and TP removal. The average removal efficiencies for NH_3-N and TN were 87.7 ± 1.4 and $70.1 \pm 1.0\%$, increased by 12.5 ± 1.0 and $8.6 \pm 0.7\%$, respectively.

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1. Introduction

Widespread demands for improved receiving water quality, especially watercourses, lakes and rivers are driving the implementation of promising tertiary wastewater treatment techniques. Many small communities located in rural areas of China lack adequate domestic wastewater treatment facilities. Wastewater collection and treatment are problematic in these areas due to mountainous terrain, dispersed population and a lower economic base. Therefore, domestic sewage was discharged directly into the receiving water, which is the reason for many serious ecological and health based problems. “New country construction” regulations in China require that the domestic sewage in rural areas must be treated before being discharged into a watercourse or soil. However, the centralized wastewater treatment plants based on activated sludge or bacterial beds processes which are utilized in large and small cities are not economically adaptable for such rural areas, mainly due to the construction costs of sewage collectors.

Subsurface wastewater infiltration system (SWIS) has been scientifically tested and constructed for on-site wastewater treatment in dispersed units and small villages [1–4]. Compared to the conventional activated sludge process, SWIS has many advantages, such as simple construction, low operation and maintenance costs, as well as simple operation [5,6]. The removal rates are generally satisfactory in terms of chemical oxygen demand (COD), biological oxygen demand (BOD_5), total phosphorus (TP) and suspended solid (SS) removal; however nitrogen removal, especially ammonia nitrogen (NH_3-N) is deficient in most of the present operating SWIS due to the insufficient amount of oxygen available to the nitrifying microbial population. Generally 60–70% NH_3-N removal was reported [3–5].

Biological nitrification–denitrification is usually the most significant nitrogen removal mechanism in the SWIS; other mechanisms such as grass uptake, substrate adsorption and ammonia volatilization are generally of less importance. The biological nitrification–denitrification process depends on various factors such as electron, dissolved oxygen (DO) availability, temperature, pH and alkalinity. The fate of nitrification is significantly lower than that of denitrification, becoming a limiting step for nitrogen removal process. The NH_3-N removal is largely dependent on the oxygen supply [7,8]. When one gram of NH_3-N is oxidized to nitrate nitrogen (NO_3-N), the sufficient oxygen required must be not less than 4.3 g. For NH_3-N with a concentration of 1 mg/L, nitrification will not occur successfully unless the DO concentration reaches 4.6 mg/L. Unfortunately, to obtain the maximum hydraulic efficiency, SWIS is always continuously fed with domestic wastewater.

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* Corresponding author.
E-mail address: graceli_2003@163.com (H. Li).

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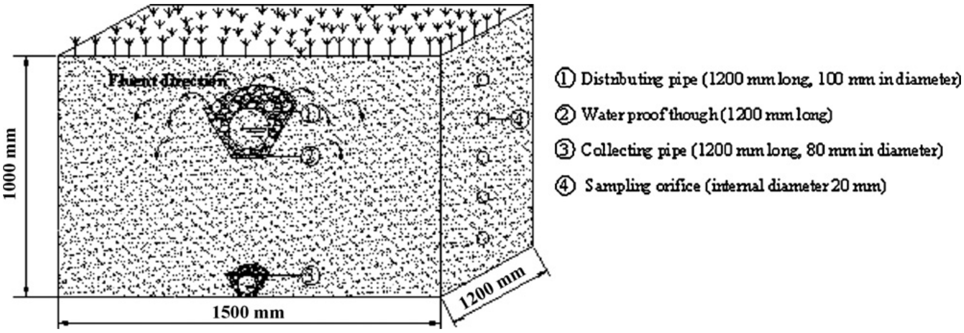

Fig. 1. Profile of a constructed subsurface wastewater infiltration system.

As such, the bed medium is water saturated and therefore generally anaerobic. In order to improve the nitrification rate, aeration is often employed to increase the concentration of DO and nitrification rate [9–13]. But with the NH_3-N removal efficiency increasing, NO_3-N concentration in the outflow will increase. On the other hand, the operation cost rises considerably.

To perform the denitrification process successfully, SWIS should have two environmental characteristics [14,15]: one is the anoxic sediments, a requisite condition for denitrification (redox potential lower than 300 mV); another is a supply of carbon source for the denitrification process. To denitrify one gram of NO_3-N to nitrogen (N_2), the organic material equivalent to 2.86 g BOD is needed [16,17]. However, decomposition of the organic matter takes place mainly in the upper part of the SWIS, resulting in the carbon source lack in the lower part and low denitrification [18–20]. So nitrogen removal via the nitrification–denitrification process may be improved if the upper part of SWIS is sufficient in oxygen for the accomplishment of the nitrification of NH_3-N; meanwhile the lower part is anoxic and carbon source is supplemented to improve denitrifying process.

Therefore, the aims of this study were:

(1) To examine the effects of alternation of wetting-drying operation on the nitrogen removal and physico-chemical parameters of the matrix.
(2) To assess the contribution of carbon source supplement on nitrogen removal, especially the shunt ratio and position.
(3) To evaluate the performance of a constructed subsurface wastewater infiltration system (CSWIS), especially the nitrogen removal under hydraulic loads of 0.040, 0.065, 0.081 and 0.10 $m^3/(m^2\,d)$, respectively. The CSWIS was designed to increase the nitrification rate by intermittent operation mode, and improve the denitrification rate by shunt distributing the sewage directly into the lower part.

2. Methodology

2.1. System description

Two parallel CSWISs, made of plexiglas, were constructed in a village in Northern Shenyang, China. The systems were 1.5 m long and 1.2 m wide with a depth of 1.0 m (Fig. 1). The matrix was 5% activated sludge, 65% brown soil and 30% coal slag mixed evenly in volume ratio. Sewage flowed through a horizontal distributing pipe, 1200 mm length and 100 mm diameter placed at a distance of 300 mm from the top of the system, with holes of 4 mm in diameter placed in the bottom every 60 mm. Effluent drained out by a perforated, 1200 mm length and 80 mm diameter circular collecting pipe, 100 mm interval from the bottom of the system, with 6 mm holes placed in the bottom side every 60 mm. Meanwhile, vertical sampling orifices (internal diameter of 20 mm) were installed at different depths: 0.1, 0.3, 0.5, 0.7 and 0.9 m below the top of the CSWISs. The beds were planted with common grass, which was mainly for landscape planting.

2.2. Raw wastewater and materials characteristics

Domestic wastewater was taken from a wastewater collector of 4 families, equivalent of 10 people (pH 7.1–7.4, COD 280–353 mg/L, BOD_5 112–140 mg/L, SS 150–200 mg/L, total nitrogen (TN) 30–45 mg/L, TP 3–4 mg/L and NH_3-N 20–30 mg/L). Soil used was meadow brown soil, sampled 0–20 cm below the soil surface, with total organics 22.8 g/kg, TN 1.4 g/kg and TP 0.85 g/kg.

The activated sludge was obtained from the aeration tanks in Shenyang Northern Municipal Sewage Treatment Plant (China), air dried after being centrifuged for 15 min at 1500 rpm (grain size 16 mesh, organic matter 57.5 mg/kg). Other materials (gravel, coal slag and sand) were purchased from a local market (in diameter: gravel 10–25 mm, coal slag 4–8 mm and sand 0.03–0.1 mm).

2.3. Analytical procedure

2.3.1. Chemical analysis

Sampling was conducted from April 2009 to August 2009. But the systems were operated 1 month before sampling to allow grass establishment and microbial biomass maturation. During the course of this study, water samples were taken from the inlet and outlet twice per week and analyzed immediately. COD, TN, NH_3-N, nitrite nitrogen (NO_2-N) and TP of the water samples were analyzed according to the standard methods [21]. Potassium dichromate method was used for COD determination; colorimetric method was used for NH_3-N, NO_3-N and NO_2-N measurements. TN of soil was analyzed by Na_2CO_3 fusion method and TP was analyzed by Kjeldahl method. Statistical analyses were carried out with MicroCal Origin 7.0 (OriginLab).

2.3.2. Measurement of nitrification and denitrification

The test medium used for measuring the potential nitrification activity (PNA) contained per litre: 0.14 g K_2HPO_4, 0.027 g KH_2PO_4, 0.59 g $(NH_4)_2SO_4$, 1.20 g $NaHCO_3$, 0.30 g $CaCl_2{\cdot}2H_2O$, 0.20 g $MgSO_4$, 0.00625 g $FeSO_4$, 0.00625 g EDTA and 1.06 g $NaClO_3$, the pH was 7.5. Sodium chlorate was used to inhibit the oxidation of nitrite to nitrate. Twenty grams of soil samples were added to 100 mL of test medium and incubated at 25 °C on a horizontal shaker at 150 rpm. Subsamples were collected after 2, 6, 20, and 24 h of incubation. PNA was calculated by angular coefficient assessment of linear regression calculated for hours and the amount of nitrate produced [20]. Results were normalized for volume loss during sampling, and expressed as mg of nitrate per kilogram dry weight (DW) per hour.

The test medium for measuring the potential denitrification activity (PDA) contained per litre: 1.44 g KNO_3, 2.0 g glucose, 27.2 g

Table 1
Contaminants removal effects of the septic tank.

Items	Influent (mg/L)	Effluent (mg/L)	Removal efficiencies (%)
SS	170 ± 1.3	59.5 ± 1.2	65.0 ± 1.5
COD	300 ± 1.0	240 ± 1.4	20.0 ± 1.0
TP	3.5 ± 0.2	3.2 ± 0.1	8.6 ± 0.6
TN	35 ± 0.7	31.3 ± 0.6	10.6 ± 0.7
NH_3-N	25 ± 1.1	23.1 ± 0.8	7.6 ± 0.2

KH_2PO_4 and 34.8 g K_2HPO_4, the pH was 7.2. Ten grams of soil samples was added to 100 mL of test medium and incubated at 25 °C on a horizontal shaker at 150 rpm. Rubber plug was used during shaking to prevent gas running out. Subsamples were collected after 48 h of incubation. PDA was calculated by angular coefficient assessment of linear regression and the amount of nitrite produced. Results were normalized for volume loss during sampling, referred to by DW and expressed as mg of nitrite per kilogram dry matter per hour.

2.3.3. *Microbial number analysis*

The nitrifying and denitrifying bacteria in the soil samples were counted using the most probable number (MPN) calculation [22]. The medium for the nitrifying bacteria contained per litre distilled water: 13.5 g Na_2HPO_4, 0.7 g KH_2PO_4, 0.1 g $MgSO_4{\cdot}7H_2O$, 0.5 g $NaHCO_3$, 2.5 g $(NH_4)_2SO_4$, 14.4 mg $FeCl_3{\cdot}6H_2O$ and 18.4 mg $CaCl_2{\cdot}7H_2O$, pH 8.0. The medium for the denitrifying bacteria contained per litre distilled water: 1.0 g KNO_3, 0.1 g Na_2HPO_4, 2.0 g $Na_2S_2O_7$, 0.1 g $NaHCO_3$ and 0.1 g $MgCl_2$, pH 8.0.

The soil samples were taken from 0.1, 0.3, 0.5, 0.7 and 0.9 m depths, respectively. Aliquot (1 mL) of serial 10-fold sterile distilled water dilutions of the soil samples were transferred to 96-cell microtiter plates containing each type of medium, then incubated at 28 °C 14 d (for the nitrifying bacteria) and 15 d (for the denitrifying bacteria), respectively. Meanwhile, 10 g of soil samples were oven-dried at 105 °C for 12 h to produce a constant weight. The amounts of the nitrifying and denitrifying bacteria were analyzed twice per month during the study.

2.4. *Experimental operation*

The sewage was pre-treated in a septic tank (effective volume of 2.0 m^3) prior to being discharged into the CSWISs to minimize the risk of clogging of pipes and the substrate [17,23,24].

During the whole experimental period, intermittent operation mode was adopted as a passive method for oxygen transfer restoring [25–27]. Each cycle of the intermittent operation included a continuous flow period of 24 h (between 9:00 am and 9:00 am the next day) and a drying period of 0, 24, 48, 72 h and 96 h, indicating wetting-drying ratio (WD) of ∞ (termed as continuous feeding mode), 1.0, 0.5, 0.3 and 0.25, respectively.

To improve the denitrification rate, a part of the wastewater was introduced to the 50 cm (method A) and 60 cm (method B) depth, with shunt ratio of 1:1, 1:2, 1:3, 2:1 and 3:1, respectively.

3. Results

3.1. *Effects of alternation of wetting-drying operation on nitrogen removal and physico-chemical parameters of the matrix*

Precipitation in the septic tank was relatively more efficient for the removal of SS than for other pollutants, NH_3-N and TN concentration changed little through this procedure (Table 1).

Table 2 describes NH_3-N and TN concentrations and removal efficiencies on discharge port under continuous and intermittent feeding modes (with different WD). Under continuous operation, NH_3-N and TN removal efficiencies were 75.2 ± 0.4 and 61.5 ± 1.3%, respectively. Under intermittent operation mode, NH_3-N removal efficiency rose from 86.2 ± 1.5% at WD 1.0 to 95.9 ± 0.4% at WD 0.25, indicating the oxidative condition of the medium was improved through the drying period of the alteration operation, which was favorable for the nitrification process. In contrast, TN removal efficiency decreased with the declining of the WD. As shown in Table 3, hydraulic conductivity, oxidation reduction potential (ORP) and the amount of the nitrifying bacteria in the sediment increased with the WD declining. On the other hand, water content and the amount of the denitrifying bacteria decreased.

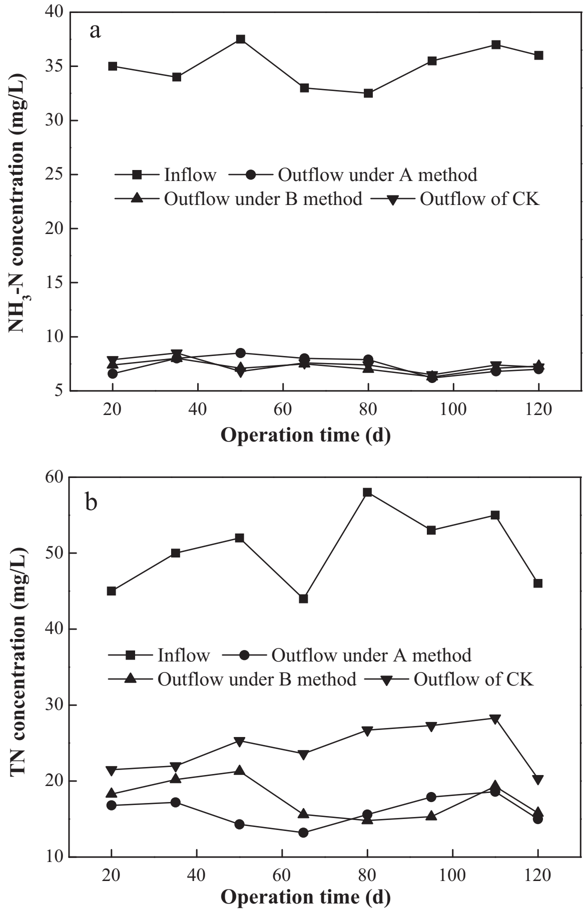

Fig. 2. Effect of shunt position on NH_3-N (a) and TN (b) concentration in the outflow.

3.2. *Effects of carbon source supplement on nitrogen removal*

As seen from Fig. 2(a), NH_3-N concentration in the effluent increased slightly due to the additional wastewater introduced, from 7.2 to 8.0 mg/L on average. On the other hand, carbon source supplement had a remarkable influence on the removal efficiency of TN. The average TN effluent concentration of CK (check) was 26.2 mg/L, with removal efficiency 50.4%. In presence of the carbon source supplement, the average TN concentration declined to 13.5 and 18.2 mg/L under method A and B, respectively (Fig. 2(b)). With respect to shunt ratio, TN removal efficiency improved by 0.23, 2.83 and 9.07% when shunt ratio being 3:1, 2:1 and 1:1, respectively after method A adopted. Meanwhile, TN removal efficiency declined by 12.2 and 30.3% than CK, respectively with shunt ratio of 1:2 and 1:3 (Fig. 3).

Table 2
Effect of operation mode (continuous and intermittent operation mode) on NH_3-N and TN removal efficiencies.

Items	Effluent (mg/L)					Removal efficiencies (%)				
	Continuous feeding mode	WD 1.0	WD 0.5	WD 0.3	WD 0.25	Continuous feeding mode	WD 1.0	WD 0.5	WD 0.3	WD 0.25
NH_3-N	12.2 ± 0.5	4.6 ± 0.3	4.0 ± 0.2	2.8 ± 0.1	1.9 ± 0.5	75.2 ± 0.4	86.2 ± 1.5	89.6 ± 0.4	93.3 ± 0.7	95.9 ± 0.4
TN	16.5 ± 1.7	8.2 ± 0.5	9.8 ± 0.1	10.5 ± 0.3	13.6 ± 1.1	61.5 ± 1.3	80.8 ± 1.8	76.3 ± 0.3	73.3 ± 0.2	70.8 ± 0.3

Table 3
Effect of wetting-drying ratio on the physio-chemical parameters of the matrix.

WD	Hydraulic conductivity (cm/s)[a]	Water content (%)	ORP (mV)	Nitrifying bacteria number (MPN/g)	Denitrifying bacteria number (MPN/g)
1.0	$(7.0 \pm 0.5) \times 10^{-5}$	35 ± 1.7	160 ± 3.8	$(1.5 \pm 0.7) \times 10^{7}$	$(7.8 \pm 0.5) \times 10^{11}$
0.5	$(9.8 \pm 1.0) \times 10^{-5}$	30 ± 2.0	190 ± 7.7	$(7.5 \pm 0.1) \times 10^{7}$	$(2.4 \pm 0.8) \times 10^{11}$
0.3	$(2.0 \pm 0.6) \times 10^{-4}$	24 ± 2.7	220 ± 10.3	$(2.1 \pm 0.8) \times 10^{8}$	$(4.5 \pm 0.4) \times 10^{10}$
0.25	$(6.1 \pm 0.7) \times 10^{-4}$	18 ± 1.8	255 ± 9.0	$(8.2 \pm 0.9) \times 10^{8}$	$(1.2 \pm 0.6) \times 10^{10}$

[a] Hydraulic conductivity was measured according to the method of Carter and Gregorich [22].

Table 4
Effect of hydraulic loads on nitrogen removal efficiencies in the CSWISs.

Hydraulic loads ($m^3/(m^2\,d)$)	Index	Influent (mg/L)	Effluent (mg/L)	Removal efficiencies (%)
0.040	NH_3-N	32 ± 5.8	0.8 ± 0.2	97.4 ± 1.8
	TN	48 ± 6.2	3.9 ± 0.5	89.8 ± 2.4
0.065	NH_3-N	43 ± 3.3	1.4 ± 0.1	92.8 ± 0.5
	TN	52 ± 7.5	6.7 ± 0.7	82.0 ± 2.9
0.081	NH_3-N	35 ± 2.0	4.3 ± 0.5	87.7 ± 1.4
	TN	48 ± 4.4	14.5 ± 1.7	70.1 ± 4.0
0.10	NH_3-N	36 ± 5.9	7.5 ± 1.0	79.2 ± 2.9
	TN	50 ± 6.6	19.7 ± 2.8	60.5 ± 3.4

3.3. *Performance of the CSWIS*

Table 4 shows the nitrogen removal efficiency in the CSWISs under WD 1.0, carbon source supplemented at 50 cm depth with shunt ratio of 1:1. NH_3-N and TN effluent concentrations increased with increasing hydraulic loads up to 0.10 $m^3/(m^2\,d)$ when soil clogging occurred. NH_3-N removal efficiency increased from 79.2 ± 2.9 to 97.4 ± 1.8%, whereas TN increased from 60.5 ± 3.4 to 89.8 ± 2.4% at the same time when hydraulic loads declined from 0.10 to 0.040 $m^3/(m^2\,d)$. Average removal efficiencies for NH_3-N and TN were 87.7 ± 1.4 and 70.1 ± 1.0%, respectively, 12.5 ± 1.0 and 8.6 ± 0.7% higher as compared with the non-intermittent and non-shunt operation mode under hydraulic loading of 0.081 $m^3/(m^2\,d)$. Meanwhile, the removal efficiencies for COD and TP were 84.8 ± 1.3 and 85.1 ± 2.0%, respectively in the CSWISs. With hydraulic load increased, the number of nitrifying bacteria in the sediment declined, while the amount of denitrifying bacteria increased, as can be seen from Fig. 4. Table 5 shows the PNA and PDA of the sediment with hydraulic loading of 0.081 $m^3/(m^2\,d)$. Average PNA and PDA values were 3.1 ± 0.2 and 2.1 ± 0.1 mg/(kg h), respectively, which were consistent with corresponding numbers of the nitrifying and denitrifying bacteria ($p < 0.05$). A quantitative estimation of the nitrifying and denitrifying bacteria and their corresponding PNA and PDA indicated higher numbers of the nitrifying bacteria than the denitrifying bacteria, and higher activity of PNA.

4. Discussion

Intermittent operation method was originated from the rapid infiltration systems, whose effects are [16,23,25,27]: firstly, as NH_3-N is the dominant types of nitrogen in the wastewater, nitrification is a limiting process for nitrogen removal from the systems. Nitrification occurred only when oxygen is present in a high enough concentration to support the growth of strictly aerobic nitrifying bacteria. Intermittent operation rather than continuous feeding is an encouraging method to ensure the DO availability for the growth of the nitrifying bacteria. Secondly, as the influent passes through the matrix, the biomat forms attached on the surface of the matrix. With the operation time goes on, soil tends to be choked by the microbial metabolites, which will shorten the lifespan of the systems. So periodic resting is adopted as a passive method for removing the microbial metabolites and restoring the hydrau-

Table 5
PNA and PDA in the CSWISs at the end of experiment.

Items	Depth (m)					Mean
	0.1	0.3	0.5	0.7	0.9	
PNA (mg/(kg h))	4.4 ± 0.2	3.5 ± 0.3	2.6 ± 0.2	2.0 ± 0.1	1.4 ± 0.1	3.1 ± 0.2
PDA (mg/(kg h))	1.0 ± 0.1	1.4 ± 0.2	1.9 ± 0.1	2.4 ± 0.1	3.3 ± 0.2	2.1 ± 0.1

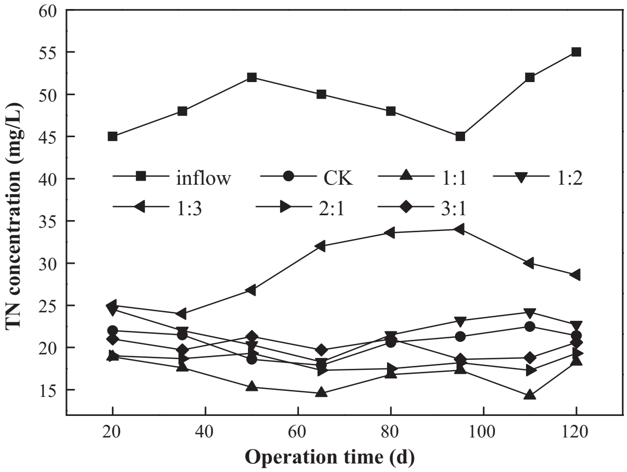

Fig. 3. Effect of shunt ratio on TN concentration in the outflow.

lic capacity. Infiltration surfaces are "rested" by removing them from service for an extended period of time. Thirdly, during the pollutants removal, especially nitrogen removal process, the produced gases such as N_2, CO_2, and N_2O will congest in and clog the soil pores, thus reduce the hydraulic capacity. Therefore, the third effect of the intermittent operation mode is to encourage the gases escaping from the systems. It is generally accepted [28–30] that DO concentrations above 1.5 mg/L are essential for nitrification to occur. In the CSWISs, 2.48 ± 0.3 mg/L DO concentration in the effluent was achieved during the study with WD 1.0, higher than the 1.0 ± 0.2 mg/L under continuous feeding mode, which was most likely resulted from the intermittent operation. As a result, NH_3-N removal efficiency increased from 75.2 ± 0.4 to 87.7 ± 1.4%, indicating that DO concentrations support nitrification. This result was consistent with much more nitrifying bacteria in the matrix.

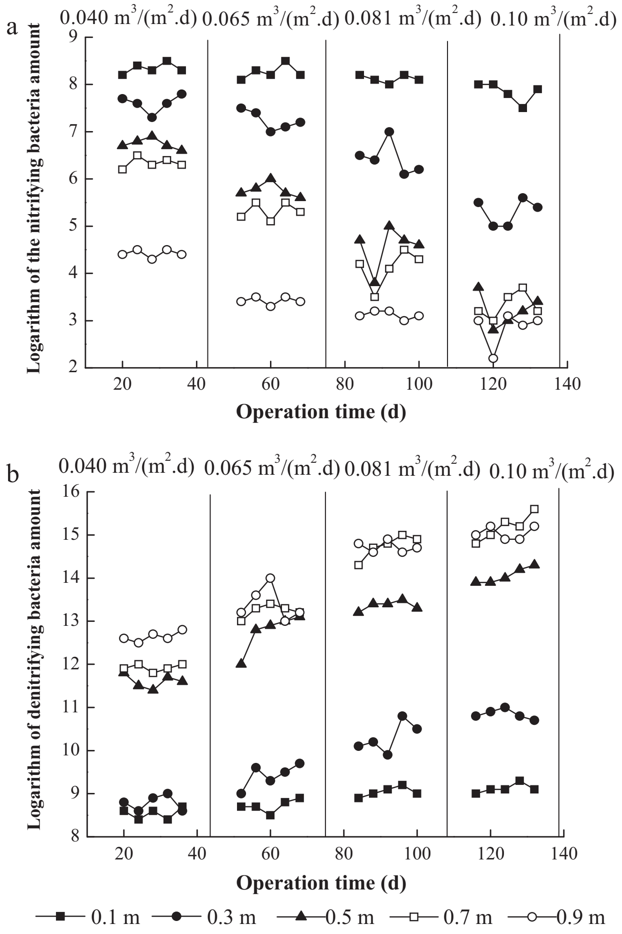

Fig. 4. Effect of hydraulic loads on distribution of nitrifying (a) and denitrifying (b) bacteria.

Table 6
Removal efficiency in the CSWISs and other studies.

Ref.	Removal efficiency (%)			
	NH_3-N	TN	COD	TP
[18]	70.0	67.7	84.7	98.0
[11]	35.6	62.3	40.4	–[a]
[1]	68.0	33.0	52.0	–
[5]	62.7	34.8	78.7	67.3
[6]	44.0	40.6	–	66.7
This study (CSWIS)	87.7	70.1	84.8	85.1

[a] Not mentioned.

Nitrification coupled with denitrification seems to be the major removal process in the CSWIS through the mechanisms as follows:

$$NH_4{}^{+} + 2O_2 \xrightarrow{\text{Nitrifying bacteria}} NO_3{}^{-} + 2H^{+} + H_2O$$
$$6NO_3{}^{-} + 5CH_3OH \xrightarrow{\text{Denitrifying bacteria}} 5CO_2 + 7H_2O + 6OH^{-} + 3N_2$$

The above chemical equations revealed that there are two major factors determining the denitrification process works well or not in the CSWIS. The first one is the redox environment, redox potential lower than 300 mV is favorable for the denitrification process [14–16]. There are studies revealed that over 80% of the total organic matters were biodegraded within the 0–25 cm soil in the infiltration systems [27,29,30]. As a result, carbon source scarceness is generally accepted as the major reason for the incomplete denitrification process [16,20]. In this study, high carbon source availability, owing to the shunt distributing wastewater directly into the depth of 50 cm, reduced competition between heterotrophs and nitrifiers. Denitrifying bacteria therefore colonized the sediment (Fig. 4(b)). TN removal efficiency increased from 61.5 ± 1.3 to 70.1 ± 1.0%. NH_3-N concentration in the effluent increased owing to the wastewater being directly introduced to the depth of 50 cm. This result suggested that shorter path of the sewage would result in the incomplete nitrification, which was in agreement of other studies [19,31]. Zhang et al. [32] noted that NO_2-N concentration in the effluent would be between 0.1 and 0.5 mg/L, thus indicating nitrification–denitrification process performed successfully in the subsurface infiltration system. Here, average 0.25 mg/L NO_2-N concentration in the effluent achieved, which was most likely resulted from the combined effect of intermittent operation and shunt distributing wastewater method. Meanwhile, as compared the removal performance of the CSWIS to other infiltration systems, CSWIS had higher nitrogen as well as comparable COD and TP removal efficiencies (Table 6), suggesting that intermittent operation and shunt distributing wastewater were simple and effective methods for nitrogen removal enhancement in the subsurface infiltration systems.

5. Conclusions

This study showed that CSWIS was effective at removing many pollutants, especially nitrogen. Passive oxygen availability accomplished by intermittent operation at WD 1.0, and shunt distributing wastewater through introducing the sewage into the depth of 50 cm with shunt ratio of 1:1, were clearly shown to be successful in improving nitrification, enhancing denitrification, respectively. The average removal efficiencies were 87.7 ± 1.4% for

NH_3-N, 70.1 ± 1.0% for TN, 84.8 ± 1.3% for COD and 85.1 ± 2.0% for TP at hydraulic loading of 0.081 $m^3/(m^2\,d)$. As compared with the non-intermittent and non-shunt operation mode, the removal efficiencies for NH_3-N and TN were increased by 12.5 ± 1.0 and 8.6 ± 0.7%, respectively with little influence on COD and TP removal. Average NO_2-N concentration in the effluent was 0.25 mg/L. PNA and PDA values were consistent with the numbers of the nitrifying and denitrifying bacteria, respectively. The above results provided an effective way to enhance nitrogen removal in the subsurface wastewater infiltration system.

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References

[1] F. Liu, C.C. Zhao, D.F. Zhao, G.H. Liu, Tertiary treatment of textile wastewater with combined medium biological aerated filter (CMBAF) at different hydraulic loadings and dissolved oxygen concentrations, J. Hazard. Mater. 160 (2008) 161–167.
[2] J. Zhang, X. Huang, C.X. Liu, H.C. Shi, H.Y. Hu, Nitrogen removal enhanced by intermittent operation in a subsurface wastewater infiltration system, Ecol. Eng. 25 (2005) 419–428.
[3] H. Arve, M. Adam, V. Lasse, A high-performance compact filter system treating domestic wastewater, Ecol. Eng. 28 (2006) 374–379.
[4] T. Glen, Wastewater management in the 21st century, J. Environ. Eng. 133 (2007) 671–677.
[5] M.K. Avinash, D.N. Pravin, G.H. Oza, H.S. Shankar, Treatment of municipal wastewater using laterite-based constructed soil filter, Ecol. Eng. 35 (2009) 1051–1061.
[6] E.H. Belinda, D.F. Tim, D. Ana, Treatment performance of gravel filter medium: implication for design and application of stormwater infiltration systems, Water Res. 41 (2007) 2513–2524.
[7] R. Kadlec, C. Ttanner, V. Hally, M. Gibbs, Nitrogen spiraling in subsurface flow constructed wetlands implication for treatment repines, Ecol. Eng. 25 (2005) 365–371.
[8] A. Michael, C. William, Nitrogen removal in recirculating sand filter systems with upflow anaerobic components, J. Environ. Eng. 133 (2007) 464–471.
[9] M. Pell, B. Stenberg, S. Hallin, Bacterial structure of biofilms in wastewater infiltration systems, Water Sci. Technol. 37 (1998) 203–206.
[10] F. Cervantes, D. Delarosa, J. Gomez, Nitrogen removal from wastewater at low C/N with ammonium and acetate as electron donors, Bioresour. Technol. 79 (2001) 165–183.
[11] G. Nakhla, S. Farooq, Simultaneous nitrification–denitrification in slow sand filters, J. Hazard. Mater. 96 (2003) 291–303.
[12] S.V. Cuyk, R. Siegrist, A. Logan, S. Masson, E. Fischer, L. Figueroa, Hydraulic and purification behaviors and their interactions during wastewater treatment in soil infiltration systems, Water Res. 35 (2001) 953–964.
[13] S. Chen, W. Song, Y. Liu, Design of wastewater reclamation and reuse by underground filtration, Water Was. Eng. 24 (2007) 32–37.
[14] F.X. Ye, Y. Li, Enhancement of nitrogen removal in towery hybrid constructed wetland to treat domestic wastewater for small rural communities, Ecol. Eng. 35 (2009) 1043–1050.
[15] J.Y. Jung, Y.C. Chung, H.S. Shin, D.H. Son, Enhanced ammonia nitrogen removal using consistent biological regeneration and ammonium exchange of zeolite in modified SBR process, Water Res. 38 (2004) 347–354.
[16] T. Rauch, J.E. Drewes, Using soil biomass as an indicator for the biological removal of effluent-derived organic carbon during soil infiltration, Water Res. 40 (2006) 961–968.
[17] H. Brix, C. Arias, M. Delbubba, Medium selection for sustainable phosphorus removal in subsurface flow constructed wetlands, Water Sci. Technol. 44 (2001) 47–52.
[18] J. Zhang, X. Huang, C.X. Liu, H.C. Shi, H.Y. Hu, Y. Qian, Pilot study on subsurface wastewater infiltration system applied in rural sewage treatment, Environ. Sci. 23 (2002) 57–60.
[19] J.L. Zou, Y. Dai, T.H. Sun, Y.H. Li, G.B. Li, Q.Y. Li, Effect of amended soil and hydraulic load on enhanced biological nitrogen removal in lab-scale SWIS, J. Hazard. Mater. 136 (2009) 816–822.
[20] X. Tang, S. Huang, S. Miklas, Nutrient removal in wetlands during intermittent artificial aeration, Environ. Eng. Sci. 25 (2008) 1279–1285.
[21] APHA, Standard Methods for the Examination of Water and Wastewater, 20th ed., American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, 1998.
[22] M.R. Carter, E.G. Gregorich, Soil sampling and methods of analysis, in: Canadian Society of Soil Science, 2nd ed., CRC Press/Taylor & Francis Group, LLC, 2006.
[23] S. Luanmanee, P. Boonsook, T. Attanandana, B. Saitthiti, C. Panichajakul, Effect of intermittent aeration regulation of a multi-soil-layering system on domestic wastewater treatment in Thailand, Ecol. Eng. 24 (2002) 415–428.
[24] B. Tunçsiper, S. Ayaz, L. Akça, K. Gunes, Performance of a pilot-scale, three-stage constructed wetland system for domestic wastewater treatment, Environ. Technol. 30 (2009) 1187–1194.
[25] M.A. Head, J.A. Oleszkiewicz, Bioaugmentation for nitrification at cold temperatures, Water Res. 38 (2004) 523–530.
[26] S. Hart, Nitrogen mineralization, immobilization, and nitrification, in: R.W. Weaver, J.S. Angle (Eds.), Method of Soil Analysis, Microbiological and Biochemical Properties, Marcel Dekker Press, New York, 1994.
[27] L. Stephanie, F. Jay, Use of an ecological treatment system (ETS) for removal of nutrients from dairy wastewater, Ecol. Eng. 28 (2006) 235–240.
[28] N.R. Siriwardene, A. Deletic, T.D. Fletcher, Clogging of stormwater gravel infiltration systems and filters: insights from a laboratory study, Water Res. 41 (2007) 1433–1440.
[29] T. Reemtsma, R. Gnirss, M. Jekel, Infiltration of combined sewer overflow and tertiary municipal wastewater: an integrated laboratory and field study on nutrients and dissolved organics, Water Res. 34 (2000) 1179–1186.
[30] C.H. Hsieh, A.P. Davis, B.A. Needelman, Nitrogen removal from urban stormwater runoff through layered bioretention columns, Water Environ. Res. 79 (2007) 2404–2411.
[31] B. Tunçsiper, S.C. Ayaz, L. Akça, Modelling and evaluation of nitrogen removal performance in subsurface flow and free water surface constructed wetlands, Water Sci. Technol. 53 (2006) 111–120.
[32] Z.Y. Zhang, Z.F. Lei, Z.Y. Zhang, N. Sugiura, X.T. Xu, D.D. Yin, Relationship between variation of nitrite-nitrogen concentration and removal efficiency for soil aquifer treatment process, J. Fudan Univ. (Nat. Sci.) 45 (2006) 755–758.