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Short communication

Effects of hydraulic loading rate on pollutants removal by a deep subsurface wastewater infiltration system

Ying-Hua Li, Hai-Bo Li*, Tie-Heng Sun, Xin Wang

Key Laboratory of Eco-remediation and Resource Reuse, Ministry of Education, Shenyang University, 21 Wanghua South Street, Shenyang, China

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ABSTRACT

The subsurface wastewater infiltration (SWI) system proved to be an effective and low-cost technique for decentralized sewage treatment in areas without adequate domestic treatment facilities. Field-scale experiments were conducted through a deep SWI system, with effective depth of 1.5 m, under hydraulic loading rates of 0.040, 0.065, 0.081 and 0.10 m^3/m^2 d. Taking the hydraulic and treatment efficiencies into consideration, the hydraulic loading rate of 0.081 m^3/m^2 d was recommended. Under this condition, NH_3–N, TN, and COD removal efficiencies were 86.2 ± 3.0, 80.7 ± 1.9 and 84.8 ± 2.1%, respectively. In the effluent, NH_3–N concentration declined to 2.3–4.4 mg/L, accounting for 63.2–65.6% of TN. NO_3–N concentration increased from 0.2 to 0.3 mg/L in the influent to 2.0–2.5 mg/L in the effluent. The nitrifying bacteria number declined with increased depth, while the amount of denitrifying bacteria increased. The analysis of results about the nitrifying and denitrifying bacteria distribution indicated that the most effective ranges for nitrification and denitrification process were 0.3–0.7 m and 0.7–1.5 m, respectively.

1. Introduction

It was estimated that 95% of decentralized wastewater around the world was discharged into the environment without any treatment (Akbulut and Saglamer, 2004; Zhang et al., 2007). Due to the deficiency of perfect sewage systems, it is more difficult to handle wastewater in rural areas than in cities.

The subsurface wastewater infiltration (SWI) system has proved to be a good alternative for on-site wastewater treatment in consideration of efficiency and cost. Because of the large demand for land area but no requirement for perfect sewage systems, its application was especially suitable for the decentralized wastewater treatment in suburbs or rural areas. Up to now, SWI technology has been widely used for wastewater treatment and reuse in the United States, Japan, Russia and other countries (Cuyk et al., 2001; Luanmanee et al., 2002; Belmlont et al., 2004; Arve et al., 2006). In SWI treatment, wastewater is first treated by conventional physico-chemical and/or biological methods and then allowed to infiltrate through an aerated unsaturated zone where it is purified through processes such as filtration, adsorption, chemical reaction and biodegradation. The removal efficiencies of organic compounds, suspended solids and phosphorus have been greater than 80% (Rauch and Drewes, 2006; Belinda et al., 2007; Zhang et al., 2007; Kadam et al., 2009). However, the SWI systems usually used in these studies were typically designed with effective depths of less than 1.0 m (ranging from 0.6 m to 1.0 m). Taking into consideration, the low temperature during November to March (average outdoor temperature subzero 18.5 °C) in Shenyang, a northeastern city of China, the design and application of a SWI system with effective depth greater than 1.0 m is necessary. The objective of this study was to concentrate on pollutants, especially nitrogen removal, by a SWI system with an effective depth of 1.5 m through a 4-month field experiment. The effect of hydraulic loading rates on pollutants removal was investigated.

2. Materials and methods

2.1. Wastewater characteristics

The influent in this study was combined wastewater, from toilets, restaurants, etc. The ranges of major water quality indices were pH 7.1–7.4, chemical oxygen demand (COD) 280–353 mg/L, biological oxygen demand (BOD_5) 160–210 mg/L, suspended solid (SS) 150–200 mg/L, total nitrogen (TN) 30–45 mg/L, total phosphorus (TP) 3–4 mg/L, ammonia nitrogen (NH_3–N) 20–30 mg/L, with an average ratio of 0.6 for BOD_5/COD.

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

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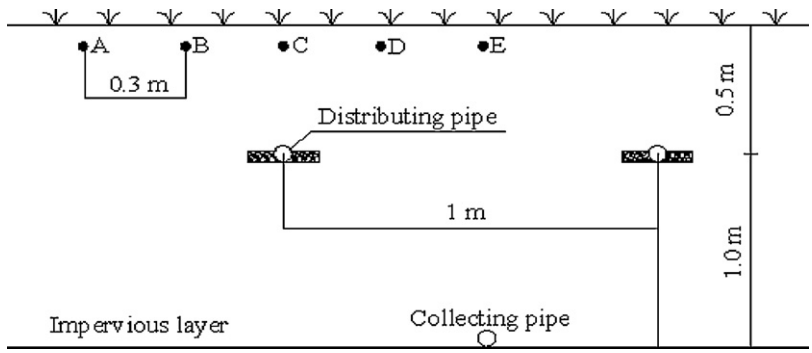

Fig. 1. Schematic diagram of the deep SWI system.

2.2. Field experiments description

The wastewater treatment process in the field experiment was composed of a pre-aeration tank, sedimentation tank and SWI system. The SWI system covered 300 m^2 (length × width = 20 m × 15 m) with effective depth of 1.5 m. The wastewater was pumped from a collecting well into the pre-aeration tank. The pre-aerated and settled wastewater flowed under gravity action into the distributing pipes, which were 0.5 m underneath of the SWI system, and then collected in the collecting pipe 1.5 m underneath. The spacing interval between distributing pipes was 1 m. In order to monitor the amounts of nitrifying and denitrifying bacteria, five sampling points (labeled as A, B, C, D and E) were arranged vertical to the distributing pipes, with intervals of 0.3 m, as shown in Fig. 1.

The field SWI system was started up in October 2009 and detailed experiments were conducted from November 2009 to February in 2010, during which intermittent operation included a feeding period of 24 h, followed by adoption of a dry period of 24 h. Four runs were arranged, with the hydraulic loads gradually elevated from 0.040 to 0.065, 0.081 and 0.10 m^3/m^2 d. Each run lasted for one month.

2.3. Matrix

The packed matrix was composed of 65% local brown soil, 30% coal slag and 5% dewatered sludge mixed evenly in volume ratio. The brown soil was collected from the top 20 cm from Shenyang Ecological Station. The coal slag was purchased from a local market in Shenyang, 4–8 mm in diameter. The activated sludge was obtained from the aeration tanks in Shenyang Northern Municipal Sewage Treatment Plant, air-dried after being centrifuged for 15 min at 1500 rpm, grainsize 16 mesh. The mixed matrix contained total organics 35.9 ± 1.2 g/kg, total nitrogen 1.8 ± 0.2 g/kg and total phosphorus 1.05 ± 0.3 g/kg, with hydraulic conductivity $(1.1 \pm 0.5) \times 10^{-4}$ cm/s.

2.4. Sampling and analytical methods

The influent and effluent samples were collected once a week, stored at 4 °C and analyzed within 24 h. COD, TN, NO_3–N, NH_3–N and TP of the water samples were analyzed according to the standard methods (APHA, 2003).

The nitrifying and denitrifying bacteria in the soil samples were enumbered using the most probable number (MPN) calculation (Carter and Gregorich, 2006). The medium for measuring nitrifying bacteria was: 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 $FeCl_3 \cdot 6H_2O$, 18.4 mg $CaCl_2 \cdot 7H_2O$ and 1L distilled water, pH 8.0. The medium for measuring denitrifying bacteria was: 1.0 g KNO_3, 0.1 g Na_2HPO_4, 2.0 g $Na_2S_2O_7$, 0.1 g $NaHCO_3$, 0.1 g $MgCl_2$ and 1 L distilled water, pH 8.0.

The soil samples were taken from 0.3, 0.5, 0.7, 0.9 and 1.1 m depths from the sampling points, 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 nitrifying and denitrifying bacteria were analyzed twice per month during the study.

3. Results and discussion

3.1. Effects of hydraulic loading rate on pollutants removal

According to batch tests of soil column (not shown here), hydraulic loading rate was an important factor influencing performance of a soil treatment system. Relatively high loading rates could not maintain stable running for the long term; relatively low loading rates would demand much soil. As seen from Fig. 2, hydraulic loading rate had obviously negative influence on the nitrogen removal in the SWI system. The average removal efficiency of NH_3–N declined from 95.2 ± 2.1% under hydraulic load 0.040 m^3/m^2 d to 77.6 ± 3.5% under 0.10 m^3/m^2 d. When the average hydraulic loading increased to 0.10 m^3/m^2 d, soil clogging occurred due to overfeeding and soil permeability decreased quickly to a small value. Great elevation of NH_3–N concentration in outflow at this condition was attributed to the deterioration of nitrification caused by soil clogging (Francisco et al., 2001; Fuentes et al., 2002; Chen et al., 2007; Daigger, 2007; Zou et al., 2009). Correspondingly, average TN removal efficiency decreased from 86.1 ± 3.3% to 60.7 ± 3.8% with the hydraulic load increasing from 0.040 m^3/m^2 d to 0.10 m^3/m^2 d. Before the soil clogging condition occurred, even when the average hydraulic load was as high as 0.081 m^3/m^2 d, NH_3–N and TN removal efficiencies were 86.2 ± 3.0 and 80.7 ± 1.9%, respectively. Therefore, to ensure the hydraulic and nitrogen removal efficiencies, hydraulic load of 0.081 m^3/m^2 d for the deep SWI system was recommended.

In the SWI system, nitrogen is removed by volatilization, adsorption, plant uptake and nitrification–denitrification (IWA, 2000; Kadlec et al., 2005). In this work, pH in the SWI system was found to be 7.5 ± 0.4. Nitrogen loss through volatilization was negligible in the study because volatilization is generally insignificant at pH below 9.3 (IWA, 2000). NH_3–N could be adsorbed on matrix in SWI system; however, such removal is not considered to be a long-term sink because the adsorbed NH_3–N is released easily when water chemistry conditions change (Kadlec and Reddy, 2001; Njau et al.,