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Nitrogen removal in subsurface wastewater infiltration systems with and without intermittent aeration

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ABSTRACT

Matrix dissolved oxygen (DO) levels, organic pollutants and nitrogen removal performances in subsurface wastewater infiltration systems (SWISs) with and without intermittent aeration operated under different organic pollutant loadings were investigated. The intermittent aeration strategy not only significantly increased removal rates of organic pollutants and NH_4^+-N, but also successfully created aerobic conditions in the depth of 50 cm and did not change anoxic or anaerobic conditions in the depth of 80 and 110 cm resulting in high TN removal. Increasing organic pollutant loading did not affect the removal of organic pollutants and nitrogen in intermittent aerated SWISs. High removal rates of COD (95.68 ± 0.21%–98.41 ± 0.23%), NH_4^+-N (93.77 ± 0.39%–98.06 ± 0.16%) and TN (84.48 ± 0.57%–94.02 ± 0.25%) were obtained simultaneously in intermittent aerated SWISs for the organic pollutant loading from 7.4 to 29.1 g COD/(m^2 d), and significantly higher than non-aerated SWISs. Intermittent aeration boosted the growth and reproduction of nitrifying bacteria and denitrifying bacteria. In the depth of 80 and 110 cm, nitrate reductase (NR) and nitrite reductase (NIR) activities with intermittent aeration were higher than that without aeration. The results suggest that intermittent aeration was a reliable option to achieve high nitrogen removal in SWISs, especially under high organic pollutant loading.

1. Introduction

Decentralized wastewater treatment around the world relies on infiltration and percolation of primary effluent through soil to achieve purification (Zou et al., 2009). Subsurface wastewater infiltration system (SWIS) is one of effective ways to treat decentralized wastewater according to integrated mechanisms of chemical, physical and biological reactions as it passes through the unsaturated soil in infiltration system (Fan et al., 2013b; Zhang et al., 2005). Compared to the conventional activated sludge and biofilm processes, this system has better performance in organic matter and phosphorus removal, lower construction and operational costs, and easier management and maintenance (Wang et al., 2010). Nitrogen removal efficiency varies greatly with wastewater quality, environmental conditions and operating conditions. Therefore, nitrogen removal remains as a major challenge for conventional SWISs (Zou et al., 2009). Nitrogen removal mechanisms in the SWIS include soil fixation, ammonia volatilization, grass uptake, nitrification and denitrification, and probable coexistence partial-nitrification of ammonium to nitrite or nitrate combining anaerobic ammonium oxidation (ANAMMOX). Among these, nitrification and denitrification are the main mechanisms responsible for eliminating nitrogen from sewage water in the SWIS (Zhang et al., 2005; Wang et al., 2010). Complete nitrogen removal relies firstly on efficient nitrification for ammonia nitrogen removal, and then requires sufficient organic carbon source in denitrification to eliminate nitrate permanently. Nitrification requires aerobic condition while denitrification occurs with anaerobic environment, which could not be fulfilled simultaneously in SWISs (Wang et al., 2010). Many studies have shown that the insufficient supply of oxygen is the major cause of limited nitrogen removal in SWISs (Zhang et al., 2005; Pan et al., 2015). Intermittent aeration has been proved to be a more cost-effective strategy, which increased TN removal efficiency by creating favorable conditions for nitrification and denitrification simultaneously (Pan et al., 2015). However, nitrogen performance was not satisfied and far above the discharge standards, when conventional SWIS was applied to treat wastewater under high organic pollutant loading (Li et al., 2012). So far, very few studies have been made to investigate the effects of organic pollutant loading on nitrogen removal performance in SWISs, especially in intermittent aerated SWISs.

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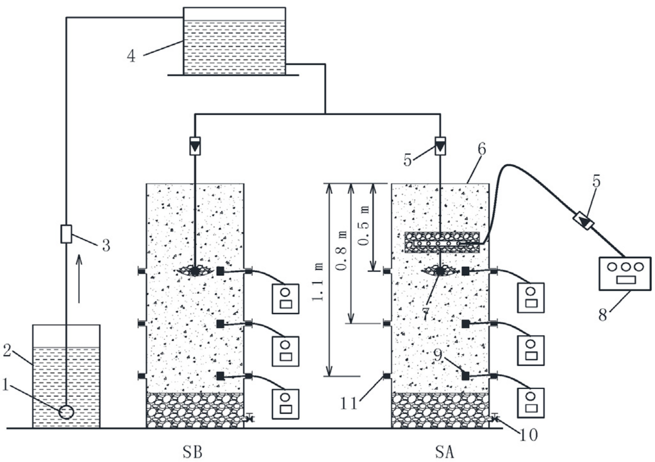

Fig. 1. Schematic diagram of two SWISs with intermittent aeration (SA) and without aeration (SB). (1) submerged pump; (2) wastewater tank; (3) control valve; (4) high-level tank; (5) flow meter (Rotor flow meter for liquid, FL-10A; Turbine flow meter for gas, RHNQ-40); (6) infiltration system body; (7) distributing pipe; (8) air compressor (with perforated diffuser); (9) DO electrodes (DN-101); (10) outlet; (11) sampling port.

Therefore, the main purpose of this paper was to investigate the effects of organic pollutant loadings and intermittent aeration on nitrogen removal performance, microbial populations and enzyme activities involved in nitrogen removal in SWISs. Moreover, matrix dissolved oxygen (DO) levels were also studied.

2. Material and methods

2.1. System description and operation

Microcosm SWISs made from clear plexiglass (120 cm in length and 50 cm internal diameter) were performed in parallel indoors, which were operated under different conditions (Fig. 1). Sampling ports were installed at 50, 80 and 110 cm from the top of the SWIS to test microbial quantity and enzyme activities involved in pollutants removal process. DO electrodes were buried in advance at the midpoint of SWISs in 50, 80 and 110 cm depth to monitor DO of pilot systems. Wastewater was continuously fed into each SWIS at a hydraulic loading of 0.06 $m^3/(m^2 d)$. Distributing pipe was installed in the depth of 50 cm below the surface. The 10 cm of deep gravel (10–20 mm, diameter) was prepared at the bottom to support infiltration system and evenly distribute the treated water. The treated wastewater was collected at the bottom of the column near the outlet. Each infiltration system filled with the same matrix made of 80% brown soil and 20% cinder in weight ratio. The physical properties of the matrix are shown in Table 1.

Six pilot SWISs were divided into three groups operated with different organic pollutant loadings (a, b, c). Every two SWISs were operated under the same organic pollutant loading, one of which was installed with aeration unit at a height of 40 cm (SA) and had four aerated/non-aerated cycles (A/N) every day. In each A/N cycle, the system was firstly subjected to aeration for one hour with an airflow rate of 2 L/min, and then had five hours interval without aeration. The aeration would begin at 0 AM, 6 AM, 12 PM, and 6 PM, respectively. The other was without aerated unit (SB).

Synthetic wastewater composed of dissolve pollutants was used in order to minimize variability in the experiment, which did not contain solids. The pollutant loading was manipulated by changing the content of glucose and formulated three different organic pollutant loadings (a) 7.4 g COD/$(m^2 d)$, (b) 14.8 g COD/$(m^2 d)$, (c) 29.1 g COD/$(m^2 d)$). Synthetic wastewater composed of 137, 245, 461 mg/L glucose; 45, 74, 163 mg/L $(NH_4)_2SO_4$; 13 mg/L KH_2PO_4; 10 mg/L $MgSO_4$; 10 mg/L $MnSO_4$; 10 mg/L $ZnSO_4{\cdot}7H_2O$; 10 mg/L $FeSO_4$ and 10 mg/L $CaCl_2$ were used in this study. The experiment began in September and lasted for more than three months in 2014.

2.2. Sampling and analytical methods

Water samples were taken from influent and effluent to analyze the transformation of organic matter and nitrogen in SWISs every ten days. COD, TN, NH_4^+-N and NO_3^--N of the water samples were analyzed according to the standard methods (American Public Health Association (APHA), 2003). Potassium dichromate method was used for COD determination. Colorimetric method was used for TN, NH_4^+-N and NO_3^--N measurements. Matrix samples were collected from sampling ports after the experiment. All samples were taken to the laboratory and analyzed immediately. The results were repeated for three times.

The nitrifying and denitrifying bacteria were counted using the most probable number (MPN) calculation (Carter and Gregorich, 2006). The medium for the nitrifying bacteria contained per liter distilled water: 13.5 g Na_2HPO_4, 0.7 g KH_2PO_4, 0.1 g $MgSO_4$, 0.5 g $NaHCO_3$, 2.5 g $(NH_4)_2SO_4$, 14.4 mg $FeCl_3$ and 18.4 mg $CaCl_2$, pH 8.0. The medium for the denitrifying bacteria contained per liter 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.

Nitrate reductase (NR) activity in the matrix was measured according to the method of Abdelmagid and Tabatabai (1987). 10 g matrix were mixed with 10 mL 1% KNO_3 and 50 mL potassium phosphate buffer (pH 7.5) at 25 °C for 24 h. The NO_2^--N produced was determined spectrophotometrically at 540 nm. The enzyme activity was expressed as the formation of NO_2^--N mg/(g d). Nitrite reductase (NIR) activity was measured as the reduction in the amount of nitrite in the assay mixture by incubating 10 g matrix with 50 mL potassium phosphate buffer (pH 7.4) and 10 mL 1% $NaNO_2$ at 25 °C for 24 h. The reduction of NO_2^--N was determined spectrophotometrically at 540 nm and the activity was expressed as NO_2^--N mg/(g d) (Abdelmagid and Tabatabai, 1987).

3. Results and discussion

3.1. DO profiles in an aerated/non-aerated cycle

DO profiles in an aerated and non-aerated cycle are shown in Fig. 2. Anaerobic and aerobic regions can be well distinguished by means of the DO profile (Fan et al., 2013b). DO concentrations greater than 2.0 mg/L are commonly interpreted as being indicative of aerobic environment, whereas less than 0.2 mg/L indicate anaerobic environment. DO concentrations between 0.5 mg/L and 0.2 mg/L are used to represent anoxic environment (Alvarez-Zaldívar et al., 2016; Wang et al., 2006). The difference was distinct between the SWISs with intermittent aeration and without aeration. Under 7.4, 14.8 and 29.1 g COD/$(m^2$ d), the aver-

Table 1
Mean physical properties of the matrix.

	Bulk density (g/cm^3)	Permeability (cm/s)	Grain-size distribution (%		
			>1 mm	0.05–1 mm	<0.05 mm
Matrix	2.2	1.23×10^{-4}	2.3	31.5	66.2