Short Communication

Effects of intermittent aeration on pollutants removal in subsurface wastewater infiltration system

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HIGHLIGHTS

• Intermittent aeration achieved high removal of COD, TP, NH4+-N and TN.
• Intermittent aeration created aerobic conditions in upper matrix.
• Microbial populations, NR and NRI activities increased in intermittent aeration.
• Intermittent aeration provided an appealing option for SWISSs.

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ABSTRACT

In this study, the pollutant removal performances in two pilot-scale subsurface wastewater infiltration systems (SWISSs) with and without intermittent aeration were investigated. Matrix oxidation reduction potential (ORP) results showed that intermittent aeration well developed aerobic conditions in upper matrix and anoxic or anaerobic conditions in the subsequent sections, which resulted in high NH4-N and TN removal. Moreover, intermittent aeration increased removal rates of COD and TP. Microbial populations and enzyme activities analysis proved that intermittent aeration not only obviously boosted the growth and reproduction of bacteria, fungus, actinomycetes, nitrifying bacteria and denitrifying bacteria, but also successfully increased nitrate reductase (NR) and nitrite reductase (NRI) in the depth of 80 and 110 cm. The results suggest that the intermittent aeration could be a widespread research and application strategy for achieving the high removal performance in SWISSs.

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1. Introduction

Subsurface wastewater infiltration systems (SWISSs) are currently a well-accepted friendly ecological process for decentralized wastewater treatment (Li et al., 2011). Satisfactory organic removal performance can be achieved and nitrogen removal efficiency varies greatly with wastewater quality, environmental conditions and operating conditions in SWISSs (Wang et al., 2010). Many studies have shown that the insufficient supply of oxygen is the major cause of limited nitrogen removal in land treatment systems (Zhang et al., 2005; Fan et al., 2013). Nowadays, treatment wetlands with active aeration have gained attention because they are capable of improving the removal of organic carbon, nitrogen and pathogens (Dong et al., 2012).

However, the artificial aeration in most studies is performed in continuous mode (Maltas-Landry et al., 2008), which always leads to contradiction between the removal of NH4-N and TN because of the lacking in favorable (i.e. alternate aerobic/anaerobic) conditions for nitrification and denitrification. Recent study report enhanced nitrogen removal by the use of intermittent artificial aeration in wetlands (Fan et al., 2013). However, so far no studies investigate on the application of intermittent aeration in a SWIS. Unfortunately, the characteristics of microbial populations and enzyme activities involved in pollutants removal are not clear about this system (Li et al., 2011). This paper focuses on a pilot-scale experiment consisting of two SWISSs treating decentralized domestic wastewater. Pollutants removal was evaluated in a side-by-side comparison of a non-aerated and an intermittently aerated SWIS in order to assess the effect of intermittent aeration. Matrix oxidation reduction potential (ORP) level, main microbial populations and enzyme activities involved in pollutants removal were also studied.
2. Methods

2.1. System description and operation

Two microcosm SWISs made from clear plexiglass (120 cm in length and 50 cm internal diameter) were performed in parallel in a greenhouse environment, which were operated under different conditions. 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. Pt electrodes coupled with calomel electrodes were buried in advance in the depth of 50, 80 and 110 cm to monitor ORP of pilot systems. 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. Wastewater was continuously fed into each SWIS at a hydraulic loading of 0.06 m³/(m² d) from a feed tank through a rubber hose with flow rate control valves. Distributing pipe was installed in the depth of 50 cm below the surface. 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.

System A (SA) was composed without aerated units. System B (SB) was installed with aeration units which consisted of air compressors, air tubes and micro-bubble diffusers at a height of 40 cm, which had four aerated/non-aerated cycles (A/N) every day. In each A/N cycle, the system was firstly subject to aeration for one hour with an airflow rate of 2 L/min, and then has five hours interval without aeration. The aeration would begin at 0 AM, 6 AM, 12 PM, and 6 PM, respectively.

The experiment began in May and lasted for more than three months in 2014. During the experimental period, temperature was 22±2°C. Wastewater from Shenyang Normal University Campus was used. The wastewater quality indexes were pH 6.7–7.5, COD 185.3–262.4 mg/L, TN 33.9–46.7 mg/L, TP 4.6–8.3 mg/L, NH₃-N 30.3–44.6 mg/L.

2.2. Sampling and analytical methods

Water samples were taken from influent and effluent to analyze the transformation of organics, phosphorus and nitrogen in two systems. COD, TN, NH₃-N, NO₃-N, NO₂-N and TP of the water samples were analyzed according to the standard methods (APHA, 2003). Matrix samples were collected from sampling ports after the experiments. All samples were taken to the laboratory and analyzed immediately. The results were repeated for three times.

The number of bacteria, fungi and actinomycetes were determined by plate count method. The removal of non-aerated system was under anoxic or anaerobic condition. In the vertical direction, previous work has suggested that the ORP decreased with depth (Zhang et al., 2005). Previous studies by Zhang et al. (2005) showed that the oxygen from air diffused to the matrix was limited and the prevailing conditions in the SWIS were anoxic or anaerobic below distributing pipe. As for the average ORP changed in SB, a similar tendency was observed for all depth, i.e. matrix ORP increased in aerated period, but decreased slowly in non-aerated period. The average ORP could be more than 181 mV during aeration and as high as 103 mV when supplementary aeration was turned off in the depth of 50 cm. However, in the depth of 80 and 110 cm, the average ORP was −48.3 and −165.7 mV during aeration, and was −104.6 and −218.8 mV without aeration. In contrast, aerobic condition was effectively developed in the depth of 50 cm and anoxic or anaerobic condition was not changed in the depth of 80 and 110 cm within SB by intermittent aeration. High aeration-induced ORP values may be reduced by the decomposition of nutrients and organic matters, which may explain the decreasing tendency in non-aerated period.

In a SWIS, organic matters were absorbed by the soil, then broken down by aerobic and anaerobic microbial processes, and mineralized as a source of energy or assimilated into biomass (Li et al., 2011). The aerobic heterotrophic bacteria played an important role in the aerobic degradation of organic matters. Domestic wastewater was richer in dissolved organic matters and disadvantageous aerobic and anaerobic environment always limited its degradation (Fan et al., 2013). Fig. 1(b) shows the COD concentrations and removal rates in the long-term experiment. The average COD effluent concentration was 19.3 mg/L, with the average removal rate 91.4% in SB and declined to 38.9 mg/L in SA. The average removal rate of COD was 81.8% in SA, with a remarkable decrease by 9.6% compared with that of SB. The intermittent aeration strategy in SB obviously improved the removal of COD, which was in accordance with other studies (Fan et al., 2012; Ong et al., 2010). Ong et al. (2010) reported that sufficient oxygen supply would greatly elevate the performance of aerobic biochemical oxidation. The intermittent aerobic conditions in SB enhanced the growth of aerobic microbes and thus facilitated aerobic removal of organic matters.

Physical sedimentation, chemical adsorption were the main ways of phosphorus removal in SWISs, which could complete instantaneously (Brooks et al., 2000). TP concentrations in effluent were all steadily under 0.45 mg/L in two systems, reflecting the effectiveness of SWISs in removing TP (Wang et al., 2010) (Fig. 1(c)). In SB, the average TP removal rate (95.9%) was a few higher than non-aerated SA (93.8%). The intermittent aeration strategy enhanced the removal of TP, which was in accordance with the aforementioned results.
failed to fulfill this first step due to insufficient oxygen supply. Therefore, nitrification is usually the limiting step for nitrogen removal (Maalais-Lundy et al., 2009).

As shown in Fig. 1(d), the average effluent NH₄-N concentration in non-aerated SA was greatly higher than that of intermittent aerated SB. Zhang et al. (2005) evaluated the removal of NH₄-N varied between 60% and 70% in continuous operation SWSs. The poor nitrification was mainly due to insufficient oxygen supply (Pan et al., 2013). Additional artificial aeration thus appeared to be the most effective alternative to substantially improve oxidation of the matrix (Maalais-Lundy et al., 2009). ORP results showed that the oxidative condition of the matrix was improved through intermittent aeration in SB, which was favorable for the nitrification process. While in non-aerated SA, the ORP was lower than −40 mV in all depth, which led to an anoxic and anaerobic environment in matrix, thus the NH₄-N removal was seriously limited. In
SB, nitrification was greatly promoted and the average NH₄-N removal rate (80.56%) was significantly higher than non- aerated SA (70.58%). What is more, four aerated/non-aerated cycles per day in present study could be able to obtain comparable NH₄-N removal rate as continuous aeration in other study (Ceng et al., 2010).

NO₃-N was the intermediate product from nitrification and denitrification process, which rooted from influent, product of NH₄-N oxidation, and denitrification of NO₂-N. Zhong et al. (2014) reported that alternating areas of aerobic, anoxic and anaerobic conditions facilitated the sequential coupling of nitrification and denitrification, and the nitrate and nitrite generated during the aerobic phase were denitrified in the anaerobic or anoxic phases. However, it would be better if the aerobic conditions occurred in the front and anaerobic or anoxic conditions occurred in the subsequent sections in matrix. As can be seen in Fig. 1(e), the average NO₂-N effluent concentrations were 0.06 mg/L and 0.21 mg/L in SA and SB, respectively. Wang et al. (2010) noted that NO₂-N concentration in the effluent would be between 0.1 mg/L and 0.5 mg/L, thus indicating nitrification–denitrification process performed successfully in SWISS. In this study, the average 0.21 mg/L NO₂-N concentration in the effluent achieved in SB, which was resulted from intermittent aeration method.

In infiltration systems, NH₄-N is firstly adsorbed on the matrix. Then, the adsorbed NH₄-N is transformed to NO₂-N under the action of nitrifying bacteria. When the nitrification process ended, NH₄-N concentration in the effluent would decline, while NO₂-N increasing. The NO₂-N must be processed via anaerobic microbial denitrification to be permanently removed from wastewater (Maltas-Landry et al., 2009). Various factors such as insufficient organic carbon source and excess oxygen could limit its completion. The average NO₂-N effluent concentrations were 9.3 mg/L and 3.2 mg/L in SA and SB, respectively (Fig. 1(f)). As shown in Fig. 1(g), the average TN removal rate was 45.8% in SA and 81.6% in SB. The low TN removal rate in SA is mainly attributed to poor nitrification, and the average NH₄-N concentration in effluent (11.2 mg/L) was much higher than SB. It could conclude that high-efficiency nitrification and denitrification were realized simultaneously in SB. In this study, intermittent aeration well developed aerobic conditions in upper matrix and anoxic or anaerobic conditions in the subsequent sections for nitrification and denitrification (Fig. 1(a)). NH₄-N could be nitrified in aerobic zones of SB and then processed via denitrification in anoxic or anaerobic zones. The needed carbon source was supplied by the continuous feeding, leading to high removal of NH₄-N and TN simultaneously.

3.2. Microbial populations and enzyme activities in two SWISS

As seen from Table 1, the number of bacteria, fungus and actinomycytes declined with depth increasing and there was a highly significant difference in most microbial populations of matrix with intermittent/non-aerated. In the same depth, the number of bacteria in SB was 100 times higher than that in SA, and the number of fungus and actinomycytes in SB was 1000 times higher than that in SA. In this study, benefiting from the intermittent aeration, oxygen could transfer to the upper matrix, which favored the growth and reproduction of bacteria, fungus and actinomycytes. The number of nitrifying bacteria declined with depth increasing. As compared, the number of denitrifying bacteria increased with the depth increasing. Benefiting from the oxygen transferring availability of the upper matrix, the zones above 50 cm were the most effective nitrifying reaction region and the denitrifying bacteria were more active below 80 cm. In oxygen-limiting environments, heterotrophic bacteria grow faster and may inhibit the development of nitrifying bacteria (Li et al., 2011). In the same depth, the number of nitrifying bacteria in SB was 1000 times higher than that in SA in the depth of 50 cm, and the number of denitrifying bacteria in SB was 100 times higher than that in SA in the depth of 80 and 110 cm. Former study also found that more nitrifying bacteria and other viable bacteria were detected in intermittent aerated systems than non-aerated systems by FISH (Fluorescence in situ hybridization analysis) (Pan et al., 2013).

Urease was an important enzyme in soil nitrogen transformation, which catalyzed the hydrolysis of urea into ammonia or ammonium ion (Pan et al., 2013). From Table 1, urease activity had no difference in the same depth of two SWISS and the higher urease activity was achieved in the depth of 50 cm benefiting from high organic nitrogen concentration here. Nitrogen in wastewater mainly existed in the state of organic nitrogen and NH₄-N, and NH₂-N was the dominant type in this study. In addition, hydrolysis of urea occurs with aerobic or anaerobic condition (Pan et al., 2013). Therefore, intermittent aeration operation had no influence on urease activity in SWISS. NR and NIR activities in soil indicate anaerobic nitrate reduction. In the process of denitrification, dissimilatory NR catalyzed the first step by reducing NO₂-N to NO₃-N and NIR catalyzed the second step by reducing NO₂-N to N₂ or N₂O (Li et al., 2011). As shown from Table 1, NR and NIR activities were influenced by matrix depth and the depth for NR and NIR activities from high to low was 110 cm (both 110 cm) in two SWISS. In the depth of 80 and 110 cm, NR and NIR activities in SB were higher than that in SA, which was in accordance with
the number of denitrifying bacteria. The oxidative condition was enhanced by intermittent aeration in the depth of 50 cm, which encouraged nitrification here. Moreover, in the depth of 80 and 110 cm, the anoxic or anaerobic conditions were not change and more NO₃⁻N or NO₂⁻N could be obtained there, which strengthens the activities of denitrifying bacteria and enhanced enzyme activities in SB. The results of microbial populations and enzyme activities could further explain the high removal of COD, NH₄⁺-N and TN in SB.

4. Conclusions

Matrix ORP results showed that aerobic conditions were effectively developed in the depth of 50 cm and anoxic or anaerobic conditions were not changed in the depth of 80 and 110 cm by intermittent aeration. The average COD, TP, NH₄⁺-N and TN removal rates were elevated from 81.8%, 93.8%, 70.5% and 45.8% without aeration to 91.4%, 95.9%, 90.6% and 81.6% with intermittent aeration. Intermittent aeration boosted the growth and reproduction of bacteria, fungus, actinomyces, nitrifying bacteria and denitrifying bacteria. In the depth of 80 and 110 cm, NR and NIR activities with intermittent aeration were higher than that without aeration.

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