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Optimization of organics and nitrogen removal in intermittently aerated vertical flow constructed wetlands: Effects of aeration time and aeration rate

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ABSTRACT

In this study, to optimize aeration for the enhancement of organics and nitrogen removal in intermittently aerated vertical flow constructed wetlands (VF CWs) for treating domestic wastewater, the experimental VF CWs were operated at different aeration time (1 h d^{-1}, 2 h d^{-1}, 4 h d^{-1}, 6 h d^{-1}, 8 h d^{-1} and 10 h d^{-1}) and aeration rate (0.1 L min^{-1}, 0.2 L min^{-1}, 0.5 L min^{-1}, 1.0 L min^{-1} and 2.0 L min^{-1}) to investigate the effect of artificial aeration on the removal efficiency of organics and nitrogen. The results showed that the optimal aeration time and aeration rate were 4 h d^{-1} and 1.0 L min^{-1}, which could create the appropriate aerobic and anoxic regions in CWs with the greater removal of COD (97.2%), NH_4^+-N (98.4%) and TN (90.6%) achieved simultaneously during the experiment. The results demonstrate that the optimized intermittent aeration is reliable option to enhance the treatment performance of organics and nitrogen at a lower operating cost.

1. Introduction

With the rapid urbanization and economic growth especially in developing countries, the decentralized domestic wastewaters in vast rural areas is generally discharged directly into water bodies due to the inadequate investment of major municipal wastewater treatment infrastructures, thus resulting in negative environmental consequences (Ongley et al., 2010; Wu et al., 2011, 2015a; Shao et al., 2014). Constructed wetland (CW), as the one of the widely used ecological technologies, has been attracted more attention as the alternative solutions for wastewater treatment in these years, owing to the advantages of good efficiency, low cost and low maintenance (Vymazal, 2011; Feng et al., 2012; Chyan et al., 2013; Wu et al., 2015b). According to water level, CWs can be classified as free water surface (FWS) CWs and subsurface flow (SSF) CWs which could be further divided into vertical flow (VF) and horizontal flow (HF) CWs. Among those kinds of CWs, VF CWs have been widely used for decentralized sewage treatment because of a higher oxygen transfer rate and adaption to cold climate (García et al., 2010; Saeed and Sun, 2012; Wu et al., 2015b).

During wastewater treatment in CWs, biological removal processes (i.e. microbial processes) play an important role in the removal of organics and nitrogen (Saeed and Sun, 2012). Oxygen availability was recognized as the crucial influencing factor for organics and nitrogen removal (Jia et al., 2011; Li et al., 2014). However, limited oxygen supply and transfer capacity in traditional VF CWs cannot generally meet the requirement for the complete removal processes of organic matter and nitrogen, particularly for treating high-strength wastewaters (Saeed and Sun, 2012; Wu et al., 2015c). Therefore, in order to improve the availability of oxygen and in turn to enhance the removal efficiency of VF CWs, artificial aeration (including continuous aeration and intermittent aeration) has been proposed as a solution to enhance the oxygen availability in CWs. Boog et al. (2014) indicated that artificial aeration increased the oxygen concentrations in both continuously

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and intermittently aerated VFCWs, and aeration significantly increased the removal of organic matter and TN. Fan et al. (2013a) reported that VF CW with intermittent-aeration achieved high removal of organic pollutants, NH_4^+-N and TN simultaneously. Moreover, artificial aeration was applied in hybrid HF CW systems to enhance the treatment performance, which showed that aeration greatly improved organics and nitrogen removal than typical HF CW (Li et al., 2014). Several studies have also focused on the effects of aeration mode, aeration period, aeration position, hydraulic loading rate and C/N ratios on the pollutants removal in aerated CWs (Jia et al., 2011; Fan et al., 2013b; Dong et al., 2012; Wang et al., 2015; Wu et al., 2015c). Nevertheless, considering the concept of sustainability based on cost–benefit analysis, CWs using artificial aeration requires additional energy input and increases the lifecycle cost, even though this approach can greatly improve treatment performance (Wu et al., 2015c). Therefore, the optimization of artificial aeration for the contaminant removal in CWs would be of great help to design more effective and sustainable CWs, and should be extensively investigated.

Due to the limited knowledge in previous literatures, the aim of this study was to investigate the optimization of organics and nitrogen removal in VF CWs for treating domestic wastewater by the use of intermittent aeration. Effects of aeration time and aeration rate on the oxygen distribution in CWs were evaluated. Moreover, the enhancing organics and nitrogen removal performance in aerated CWs was examined in detail. It is expected that the results from this study will offer a reference for successful application of intermittently aerated CWs at a low capital cost.

2. Material and methods

2.1. Site and system description

The experiment was carried out in Baihua Park in Jinan, China as described in detail by Wu et al. (2015b). Eleven parallel microcosm VF CWs were constructed for treating simulated domestic wastewater in this study. Six systems were for the optimization experiment of aeration time and the others were for the optimization experiment of aeration time. Each system was made of PVC plastic pipe with a height of 65 cm and a diameter of 20 cm. Multi-dimensional gradation of the substrate and porous air spargers were used for oxygen supply and oxygen diffusion as described in detail by Fan et al. (2013c). A vertical perforated PVC pipe was installed into the substrate in the center of VF CWs in order to measure various physical and chemical parameters in situ. Each system was planted in May 2014 with healthy *P. australis* (at a density of eight rhizomes per system). The systems were submerged in tap water immediately after planting to allow the development of plants and microbes until June 2014, and then the systems started operation.

2.2. Experimental procedure

In June 2014, the systems were mainly mature, and were continuously fed with wastewater to start the experiment. To minimize the influence of the fluctuation of influent water quality, the influents were synthetically prepared using sucrose, $(NH_4)_2SO_4$, KH_2PO_4, $MgSO_4$, $FeSO_4$ and $CaCl_2$ in this study. Table 1 shows the composition of the synthetic influent in terms of COD, NH_4^+-N, NO_3^--N, NO_2^-N,TN and TP. In the optimization experiment of aeration time, six systems were operated and intermittently aerated with an airflow rate of 1.0 L min^{-1} for 1 h d^{-1}, 2 h d^{-1}, 4 h d^{-1}, 6 h d^{-1}, 8 h d^{-1} and 10 h d^{-1}, respectively. Based on the optimal aeration time, the other systems were operated and intermittently aerated with the aeration rate of 0.1 L min^{-1}, 0.2 L min^{-1}, 0.5 L min^{-1}, 1.0 L min^{-1} and 2.0 L min^{-1} for the optimization experiment of aeration time. The hydraulic retention time (HRT) was 72 h, which just a cycle in this study, and the depth of water in each system was approximately 60 cm. Sequencing fill-and-draw batch mode was used for influent mode. At about 8:00 am on the first day of each cycle, the influent was supplied in batch mode into each VFCW within 15 min. Effluent was discharged from the outlets at the bottom of VFCWs. The average air temperature generally ranged from 23 °C to 32 °C during the experimental period in this study.

2.3. Sampling and analysis

Water samples of influent and effluent at different time were taken to analyze the transformation of organics and nitrogen in eleven reactors. The samples were taken to the laboratory and analyzed immediately for NH_4^+-N, NO_3^--N, NO_2^--N and TN according to standard methods (APHA, 2005). COD was measured by a HACH DR 2008™ Spectrophotometer, USA. In each cycle, after the influent was supplied into each CW, dissolved oxygen (DO) was measured at the midpoint of the water depth from the vertical perforated PVC pipe by a DO meter (HQ 30d 53LED™ HACH USA) until effluent was discharged from the CW at the end of the cycle.

2.4. Statistical analysis

All statistical analyses were performed by the statistical program SPSS 11.0 (SPSS Inc., Chicago, USA). The tables and figures show the results of averaged data, Two-sample *t*-tests were used to evaluate the significance of differences between means. In all tests, differences and correlations were considered statistically significant when $P < 0.05$.

3. Results and discussion

3.1. Optimization of aeration time for treatment performance

3.1.1. DO distribution in systems during experimental cycle

Fig. 1 shows the cyclic distribution of DO in the intermittently aerated VF CWs with different aeration times. According to Fig. 1, intermittent aeration enhanced the oxygen availability for all wetland systems during the period of aeration with various aeration times, however, the variation and fluctuation of DO concentrations was observed to be significantly distinct in different systems during the course of different aeration times. The influent DO concentration was approximately 7.65 mg L^{-1}, and the DO concentrations in all systems decreased immediately in the initial phase due to fast consumption of oxygen for the removal of degradable pollutants. While the alternate increase (6–8 mg L^{-1}) and decrease of DO concentrations were developed as the sequence of intermittent aeration was applied, indicating that the cyclic anaerobic and aerobic conditions were formed successfully in

Table 1
Water quality parameters of the influent during the experimental period.

Parameters	COD	NH_4^+-N	NO_3^--N	TN	TP	DO	pH
Influent (mg L^{-1})	426.23 ± 13.83	39.65 ± 0.61	4.35 ± 0.17	44.12 ± 0.79	4.52 ± 0.35	7.65 ± 1.12	7.58 ± 0.82