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Improving removal performance of pollutants by artificial aeration and flow rectification in free water surface constructed wetland

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ABSTRACT

Improving the removal performance of pollutants in constructed wetlands (CWs) is a very important topic. In this work, artificial aeration and flow rectification were used to enhance the pollutant-removal efficiencies of free water surface (FWS) CW in treating campus wastewater. Experimental results demonstrated that, under a rather low average concentration of biochemical oxygen demand (BOD < 12.3 mg l^{-1}), artificial aeration and flow rectification showed a superior potential in increasing the removal ratio of BOD from 46.7% to 68.3% on school days and from 13.2% to 46.7% on non-school days. An effective increase in ammonium-nitrogen (NH_4^+—N) removal from 32.9 – 54.8% to 78.2 – 78.6% was achieved. Also, great improvements in removal loading rates to 4.498 g-N d^{-1} m^{-2} and 1.738 g-N d^{-1} m^{-2} under influent loading rates of 5.750 g-N d^{-1} m^{-2} and 2.211 g-N d^{-1} m^{-2} on school days and non-school days, respectively, enlarged emerging applications of FWS CWs. It implied that artificial aeration and flow rectification increased the efficiency of land use in FWS CWs and reduced the cost of pollutant removal. No significant effects of artificial aeration on total phosphorous (TP) removal performance were observed. From the experimental results with artificial aeration and without flow rectification, it demonstrated that proper flow rectification was crucial in using aeration to improve the removal performance of FWS CWs. The resuspension of sediments that was induced by aeration worsened the removal performances of BOD and NH_4^+—N but improved the removal of TP by improving adsorption and sedimentation.

1. Introduction

Constructed wetlands (CWs) have been regarded as a green technology of wastewater treatment and environmental remediation because of their minimal need for fossil energy, and associated low operational costs (Saeed and Sun, 2012; Zhang et al., 2010). Owing to these unique advantages, the use of CWs in treating wastewater or remediating eutrophic water has increased rapidly around the world (Kadlec and Knight, 1996; Saeed and Sun, 2012; Vymazal, 2007). Investigations of the pollutant removal performance have shown that the removal efficiencies of organic pollutants exceed those of pollutants that contain nitrogen (N) and phosphorous. The removal ratio of total nitrogen (TN) by CWs varies between 40 and 55%, with removal loading rates from 0.685 g-N d^{-1} m^{-2} to 1.726 g-N d^{-1} m^{-2}, whereas the removal ratio of total phosphorous (TP) is in the range of 40 – 60% with removal loading rates of between 0.123 g-N d^{-1} m^{-2} and 0.205 g-N d^{-1} m^{-2}. Nitrogen removal is thus relatively low (Cottingham et al., 1999; Vymazal, 2007; Zhang et al., 2011). In Europe, the removal efficiencies of ammonia-nitrogen (NH_3—N) and TN by 268 wetlands are 30.0% and 39.6%, respectively (Zhang et al., 2011). Therefore, N removal is one of the most important aspects of improving the performance of CWs. Various mechanisms are responsible for nitrogen removal, included volatilization, ammonification, anaerobic ammonia oxidation (ANAMMOX), nitrification/denitrification, plant uptake and adsorption. Nitrification/denitrification, sedimentation burial and plant uptake are responsible for 54 – 96%, 0 – 46% and 7.5% –14.3% of the removal of N in CWs, respectively. Nitrification/denitrification has generally been regarded as the main mechanism of nitrogen removal (Chen et al., 2014; Green et al., 1998; Kadlec and Knight, 1996; Lin et al., 2002; Vymazal, 2007).

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Although the environmental factors that affect the removal performance of N by nitrification/denitrification include temperature (T), pH, dissolved oxygen (DO), oxidation-reduction potential (ORP) and electrical conductivity (EC) (Saeed and Sun, 2012; Vymazal, 2007), low DO in the influent causes incomplete nitrification and yields high concentrations of TN in the effluent (Dong et al., 2012). Artificial aeration to increase DO supply has become a promising modification improving the pollutant removal efficiency of CWs (Cottingham et al., 1999; Green et al., 1998). Experimental results concerning nitrification and corresponding oxygen consumption agree closely with theoretical calculations that are based on physicochemical considerations. The removal ratios of influent nitrogen loads in planted and unplanted subsurface flow (SSF) CWs increase from approximately 14 − 45% and 10 − 67% to approximately 51 − 98% and 20 − 59%, respectively. However, high DO suppresses the denitrification process and results in high concentration of nitrate-nitrogen (NO_3^-−N) in the effluent (Cottingham et al., 1999; Green et al., 1998; Nivala et al., 2007; Tao and Wang, 2009). Related studies yields accumulation ratios of NO_3^-−N ($R_{ac\text{-}\bar{N}O3\text{-}N}$), defined as the ratio of the highest concentration of NO_3^-−N to the concentration of ammonium nitrogen (NH_4^+−N) in the influent, from 25.8% to 100%. However, other studies have found the absence of NO_3^--N accumulation in the effluent of SSF CWs with artificial aeration (Ong et al., 2010; Ouellet-Plamondon et al., 2006; Zhang et al., 2010). Artificial aeration significantly enhances the removal of NH_4^+−N in SSF CWs, increasing COD/N, which is the ratio of the influent chemical oxygen demand (COD) to the concentration of NH_4^+−N, from 0:1 to 5:1. A large COD/N implies that an additional carbon source positively affects N transformation. In contrast, a high concentration of NO_3^-−N has been observed at a low COD/N ratio with DO depression on denitrification (Ding et al., 2012; Liu et al., 2013).

Artificial aeration is promising not only in improving N removal but also in degrading of organic pollutants in cold climates (Nivala et al., 2007; Ouellet-Plamondon et al., 2006). However, since CWs remove organic pollutants more efficiently than they remove N, adding DO does not promote the removal of organic pollutants (Liu et al., 2013; Nivala et al., 2007, 2005; Zhang et al., 2010). The removal of phosphorous involves peat/soil accretion, adsorption/desorption, precipitation/dissolution, plant/microbial uptake, fragmentation and leaching, mineralization and burial. Soil adsorption and peat accretion are responsible for long-term phosphorus sequestration in wetlands (Vymazal, 2007). Introducing artificial aeration into SSF CWs generates additional DO and turbulence, which affect the removal of TP. One study reported no significant change in total phosphorous (TP) removal with the introduction of artificial aeration (Zhang et al., 2010). According to the field results of Lin et al. (2015), artificial aeration increases the removal ratio of TP from 55.6% to 82.1%, implying that aeration in the SSF CW affects the transformation mechanisms of TP in various ways.

Most works on improving pollutant removal efficiencies using artificial aeration have been performed in SSF CWs, which are discussed above. The disturbance induced by artificial aeration may turn the flow pattern in a CW from laminar to turbulent. Turbulent flow negatively affects some of the mechanisms that are responsible for pollutant removal in CWs. Baffles have been utilized to minimize the channelization of water flow in free surface water (FWS) CWs and to dampen the turbulence that is induced by artificial aeration. In the work of Jamieson et al. (2003), aeration increases NH_4^+−N removal from 51% to 93%. This improvement implies that artificial aeration in FWS CWs is an effective means of enhancing pollutant removal efficiency, even though $R_{ac\text{-}\bar{N}O3\text{-}N} = 64.8\%$. The long hydraulic retention time (HRT) of 11 days in the study of Jamieson et al. (2003) is responsible for the high cost of CWs land. However, the shear force that is induced by artificial aeration may separate a biofilm from the surface of the substrate in an SSF CW. Increasing the amounts of suspended solids and air bubbles severely worsened nitrification performance (Hu et al., 2012; Nivala et al., 2007). In this study, a flow rectification system that had a honeycomb-like structure was installed in an FWS CW to eliminate the disturbance that would otherwise be induced by artificial aeration. The parameters of water quality, BOD, NH_4^+−N, and TP, were used to evaluate the removal performance of pollutants by FWS CW and the improvement that was afforded by artificial aeration and flow rectification.

2. Materials and methods

2.1. Setup of experimental CW models

In this work, two experiments were designed to investigate the improvement of artificial aeration and flow rectification and the effect of rectification on pollutant removal by FWS CW. In the former experiment that comprised an influent tank, FWS CW, and an effluent tank, laboratory-scale FWS CW systems were established as shown in Fig. 1. System A (FWS-A) included artificial aeration and honeycomb rectification. System B (FWS-B) was the control system without aeration and rectification. Both systems had the same dimensions −2.0 m long, 0.6 m wide and 0.5 m high. The water depth was maintained at 0.3 m in both systems, and the bottom soil, with a depth of approximately 15 cm, was used to grow the aquatic plant, Cattail (*Typha orientalis Presl.*). A sinking pump for artificial aeration was installed in the inflow area, which was approximately 20 cm long. Since the inflow area was limited, the DO levels for various combinations of artificial aeration were examined, because a DO concentration of over 1.5 mg l^{-1} was essential for nitrification (Liu et al., 2013; Vymazal, 2007). Based on a constant air flow rate of 111 l m^{-3} min^{-1}, artificial aeration with a sinking pump maintained an average DO concentration of 2.2 mg l^{-1} in the effluent of system A. The average DO of system B was approximately 0.65 mg l^{-1}. The honeycomb for flow rectification was composed of approximately 4900 straw pipettes, each with a diameter of 5 mm and a length of 10 cm. A cover over artificial aeration and honeycomb rectification suppressed the growth of algae.

To investigate the effects of flow rectification on the removal of pollutants, a FWS CW (FWS-C) with artificial aeration but without honeycomb rectification was established and aeration rate maintained 50 l m^{-3} min^{-1} during the experimental period. A FWS-D without aeration and rectification was also established as a control system. The dimensions and operational parameters were similar to those in the experiments with FWS-A and FWS-B systems. Cattails were also planted in FWS-C and FWS-D CWs.

2.2. Model operations and data analysis

The experiment of FWS-A and FWS-B was conducted for 464 days to investigate the improvement of the pollutant removal performance of FWS CW that was provided by artificial aeration and flow rectification. The campus wastewater was used as the influent of the experimental CW with a hydraulic loading of 1.8×10^{-1} m d^{-1} and a HRT of 1.67 d. The experimental period included the school in session (SP) and not in session (NSP). There were 18 weeks for a SP. On SP, intensive teaching activities resulted in a higher average BOD loading (2.21 g d^{-1} m^{-2}) in the influent than that (9.46×10^{-1} g d^{-1} m^{-2}) on NSP, which included summer vocation or winter vocation. A preliminary experiment was performed to ensure that the FWS-A and FWS-B CWs were stable in the experiments. Artificial wastewater with a constant