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Simultaneous improvement of waste gas purification and nitrogen removal using a novel aerated vertical flow constructed wetland

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ABSTRACT

Insufficient oxygen supply is identified as one of the major factors limiting organic pollutant and nitrogen (N) removal in constructed wetlands (CWs). This study designed a novel aerated vertical flow constructed wetland (VFCW) using waste gas from biological wastewater treatment systems to improve pollutant removal in CWs, its potential in purifying waste gas was also identified. Compared with unaerated VFCW, the introduction of waste gas significantly improved NH_4^+-N and TN removal efficiencies by 128.48 ± 3.13% and 59.09 ± 2.26%, respectively. Furthermore, the waste gas ingredients, including H_2S, NH_3, greenhouse gas (N_2O) and microbial aerosols, were remarkably reduced after passing through the VFCW. The removal efficiencies of H_2S, NH_3 and N_2O were 77.78 ± 3.46%, 52.17 ± 2.53%, and 87.40 ± 3.89%, respectively. In addition, the bacterial and fungal aerosols in waste gas were effectively removed with removal efficiencies of 42.72 ± 3.21% and 47.89 ± 2.82%, respectively. Microbial analysis results revealed that the high microbial community abundance in the VFCW, caused by the introduction of waste gas from the sequencing batch reactor (SBR), led to its optimized nitrogen transformation processes. These results suggested that the VFCW intermittently aerated with waste gas may have potential application for purifying wastewater treatment plant effluent and waste gas, simultaneously.

1. Introduction

Constructed wetland (CW) is an environmentally sustainable, socially accepted and cost-effective wastewater treatment technology which shows a strong potential for better secondary effluent treatment (Greenway, 2005). Ávila et al. (2015) found that the effluent treated by hybrid constructed wetlands could meet all the requirements for reclaimed water in Spain. However, the insufficient oxygen supply in traditional CWs often hinders their treatment efficiencies, especially for organic matter and ammonium (Hu et al., 2012). Artificial aeration and tidal flow (the operation of intermittently flood and drain) have been developed as major dissolved oxygen (DO) optimization processes (Liu et al., 2016). Even though artificial aeration is considered to be the most effective method to ensure sufficient oxygen supply, the corresponding operational costs greatly limit its popularity (Zhang et al., 2010). Tidal flow is also a method used to address oxygen transfer limitations (Wu et al., 2011). However, the oxygen supply efficiency of tidal flow is lower than that of artificial aeration (Wu et al., 2014). Jia et al. (2010) found that removal rates of ammonia nitrogen and chemical oxygen demand (COD) generally increased during the tidal flow operation, although TN removal decreased as a result of the accumulation of nitrate. Hence, it is important to further optimize the wetland oxygen supply strategy.

The seriously deteriorated water environment lead to more stringent wastewater discharge standards. For example, the government released Water Pollution Control Action Plan in April 16, 2015, to guide water pollution control in China. At present, many wastewater treatment plants (WWTPs) in China have been required to meet third-grade surface water standard. However, in most cases, WWTPs are unable to meet the requirements of these new guidelines. Hence, to effectively remove pollutants, such as organic matter and ammonia nitrogen, intensive aeration is

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implemented in traditional biological wastewater treatment processes, which accounts for 40–60% of the total operating costs of WWTPs (Gu and Song, 2008). Additionally, the waste gas produced from aeration often goes directly into the atmosphere, resulting in a nuisance to adjacent populations and serious environmental pollution risks, including odorous gases (Burgess et al., 2001), high emissions of greenhouse gases (mainly nitrous oxide (N_2O) (IPCC, 2013)) and microbial aerosols (Brandi et al., 2000). N_2O is an important greenhouse gas that can also cause ozone depletion in the stratosphere. Its 100-year global warming potential is 298 times higher than that of carbon dioxide (CO_2). Microbial aerosols have caused concern all over the world. Brenner et al. (1988) reported the distribution of animal viruses, bacteria and phages in the atmosphere around a sewage irrigation station. In addition, the microorganism aerosol threshold limit value is very important for human health risk assessments (Srikanth et al., 2008). Waste gas emission from biological wastewater treatment has become a serious concern. It should be better controlled or, if possible, utilized to protect the urban environment.

A range of technologies has been developed to purify waste gas, which can be roughly classified as three categories (Burgess et al., 2001; Kennes and Veiga, 2001), biological (biofilters, bioreactors), chemical (chemical scrubbers, thermal oxidation, catalytic oxidation, ozonation), and physical (condensation, activated carbon, clean water scrubbers). However, the present waste gas purification technologies involve long and complex treatment processes, and more important, waste of resources and energy. Few literatures are found to describe how waste gas can be utilized as a kind of "available resource". Therefore, it is of great interest to develop novel aerated CWs, which can efficiently recycle resources and minimize gaseous pollution, simultaneously.

In this study, the vertical flow constructed wetland (VFCW) was aerated by using waste gas from a sequencing batch reactor (SBR). Specific objectives were: 1) to analyze the feasibility of using waste gas to enhance oxygenation of a VFCW; 2) to evaluate the removal efficiency of waste gas ingredients (including odorous gases, greenhouse gas and microbial aerosols) via a VFCW; and 3) to elucidate the mechanisms of pollutant removal in novel aerated VFCW.

2. Materials and methods

2.1. Experimental system configuration

The lab-scale systems were located at Shandong University in Jinan, China (36°40′36″N, 117°03′42″E). The experiment was kept running from March 23, 2016 to November 3, 2016. The systems were composed of a SBR followed by three parallel laboratory-scale VFCWs (System I: unaerated VFCW; System II: VFCW intermittently aerated with air; and System III: VFCW intermittently aerated with waste gas). The schematic diagram of the experimental setup is shown in Fig. 1.

The effective volume of the anoxic/aerobic SBR was 15 L. The internal diameter and working height of the reactor were 25 and 30 cm, respectively. The schematic design of the reactor has been reported by Zhang et al. (2015). The influent wastewater was prepared in a storage tank (100 L) and introduced into the SBR using a peristaltic pump. The DO was supplied by using an air pump through an air diffuser at the bottom of the reactor. The SBR was intermittently aerated at an airflow rate of 0.12 m^3/h. The seeding sludge was obtained from the Second Wastewater Treatment Plant of Everbright Water (Jinan) Ltd. China. After one month of operation, the concentrations of pollutants in effluent tended to be stable and the SBR-VFCWs were in a steady state. The mixed liquor suspended solid (MLSS) of the SBR was maintained at 4500–5000 mg/L.

The lab-scale VFCWs (Systems I, II and III) were constructed outdoors (25 cm in length, 25 cm in width and 50 cm in depth) with an outlet at the bottom. A dimensional gradation substrate was adopted, which was made of a 10 cm bottom layer of gravel (3–4 cm in diameter) that served as the supporting layer; silica sand (2–3 cm in diameter) as the main substrate layer that was filled in each wetland, with a depth of 30 cm; and a 10-cm top layer of washed river sand (1–2 mm in diameter) that was added for facilitating the dispersion of wastewater and growth of plants. To measure various physical and chemical parameters *in situ*, a vertical perforated PVC pipe (60 cm in length and 3 cm in diameter) was inserted into the substrate in the middle of the VFCWs. In System II and System III, the porous air sparger was installed in the bottom supporting layer of each system for oxygen supply. In this study, sweet flag (*Acorus calamus* L.) was selected as the experimental plant. Sweet flag, which is an emergent macrophyte colonizing littoral zones of eutrophic habitats, has been used in naturally occurring and constructed wetlands to treat wastewater (Brändle et al., 1996). Healthy plants with a similar size (approximately 30 cm in height) were weighed and then transplanted into the VFCWs at a density of 20–25 rhizomes per unit. In this study, the size of VFCW units is 25 cm in length and 25 cm in width. According to the density ranges observed in natural aquatic environments, a spacing of sweet flag was set to 5 cm, resulting in 20–25 rhizomes per unit. After transplanting, CW microcosms were fed with the SBR effluent for one month before the experiment started, until wetland plants and microorganisms were well established.

2.2. Experimental procedure

The SBR was fed with synthetic wastewater prepared from tap water. The composition of synthetic wastewater is as follows (per liter): sucrose (133.90 mg), starch (115.40 mg), NH_4Cl (114.64 mg), $(NH_4)_2SO_4$ (141.60 mg), $K_2HPO_4\cdot 3H_2O$ (18.00 mg), KH_2PO_4 (11.00 mg), $CaCl_2\cdot 2H_2O$ (10.00 mg), $MgSO_4$ (5 mg), $FeSO4\cdot 7H_2O$ (10.00 mg) and a trace element solution (1.0 mL). The composition of the trace mineral solution was derived based on previous literature (Tay et al., 2002). The COD and NH_4^+-N concentrations of the synthetic wastewater were approximately 300 and 60 mg/L, respectively. The influent pH values were adjusted to 7.5–8.0 by adding $NaHCO_3$. The SBR was operated at a volumetric exchange ratio of 50%, with a cycle of 4 h, resulting in a hydraulic retention time (HRT) of 8 h. Each cycle was consisted of 10 min for filling influent, 60 min for the anoxic process, 120 min for the aeration reaction, 30 min for settling, and 20 min for decanting the effluent.

The effluent of the SBR flowed into a setting tank and was subsequently conveyed to the beds of three VFCWs, at a flow rate of 7 mL/min to keep the water level below the sand surface, by using a peristaltic pump. Treated effluent was discharged from the outlet at the bottom of each VFCW. Each wetland was operated continuously at HRT of 1 day. The characteristics of the influent were periodically monitored during the experimental period. Systems II and III were intermittently aerated, which was consistent with the SBR aeration time. System I was operated without aeration.

2.3. Sample collection and analysis

2.3.1. Water quality monitoring

Water samples were taken from the influent and effluent of the SBR and from the effluent of the three VFCWs every 3 days to analyze the transformation of organic matter (COD), phosphorus (P) and nitrogen (N). Water samples were then analyzed immediately for NH_4^+-N, NO_3^--N, NO_2^--N, TP, TN and COD. The DO concentration was determined *in situ* with a DO meter (HQ30d, Hach,