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Optimizing the operation of combined oxidation pond-constructed wetland ecosystems used for treating composite wastewater

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ABSTRACT

Given few studies refer to the employment of constructed wetlands to polish secondary effluent and purify runoff simultaneously prior to replenishment of surface water, lab-scale combined oxidation pond-constructed wetland ecosystems used for treating the composite wastewater were established in this study, and the effects of four factors, each at four levels, on the treatment efficiency of the system were investigated through orthogonal experiment. The tested factors were (i) ratio of five-day biochemical oxygen demand (BOD_5) to chemical oxygen demand (COD_{Cr}) (abbreviation B/C) in the influent, (ii) aeration position, (iii) aeration intensity (expressed as air/water ratio), and (iv) hydraulic residence time (HRT). Results showed that the sequence and degree of the influence of the tested factors were HRT** > aeration intensity** > aeration position* > B/C for COD_{Cr} removal, HRT** > aeration position* ≈ aeration intensity* > B/C for ammonia (NH_4^+-N) removal, HRT** > B/C** > aeration position** > aeration intensity** for total nitrogen (TN) removal and HRT** > aeration intensity > aeration position ≈ B/C for total phosphorus (TP) removal (* denotes significant influence ($0.01 < p < 0.05$) and ** denotes extremely significant influence ($p \leq 0.01$)). Although the optimal operating conditions for COD_{Cr}, NH_4^+-N, TN and TP removal in the system were quite different from each other, the comprehensive optimal operating conditions (B/C ≈ 0.30, surface aeration, aeration intensity = 3:1, HRT = 2.0 d) obtained by the comprehensive balance method for the operation of the whole system proved to be feasible and practicable, under which the average concentration removal percentages were 80.81%, 75.97%, 82.38% and 80.95% for COD_{Cr}, NH_4^+-N, TN and TP, respectively. Moreover, the wetland columns accounted for the greatest removal of pollutants in the combined system, while the oxidation pond conferred a buffer capacity to the system by allowing for high loading fluctuations and pre-treated the influent as well. This study also offers references for the analysis of the results of the multi-index orthogonal test.

1. Introduction

Tap water, precipitation and secondary effluent from wastewater treatment plants (WWTPs) are common supplemental sources of water for surface water (rivers, lakes, etc.) suffering from water shortage. All the three supplemental water sources have their own advantages and disadvantages. For tap water, the water quality is the best but the cost is the highest. Generally it is unaffordable to replenish surface water only with tap water, especially when the amount of supplementary water needed is relatively large. Precipitation and surface runoff are completely free but the water quality is the worst. Davis et al. (2001) and Lee et al. (2002) reported that from washing off road surfaces, parking areas, vehicles and building materials, precipitation and surface runoff contain a broad spectrum of pollutants, including suspended solids, heavy metals, nutrients and organics, especially during the first flush. Stormwater runoff has been identified as one of the leading causes of degradation in the quality of receiving waters (Kivaisi, 2001; Lee et al., 2002). Therefore, there is a great need for the runoff quality to be improved before discharge into open water bodies. Moreover, for regions with less precipitation, the needs of replenishment could hardly be satisfied only by precipitation and runoff. With the advantage of successfully recycling water resources and greatly saving costs, the secondary effluent continuously produced from WWTPs appears to be the most feasible choice. However, the effluent generally still contains high levels of nutrients and organic matter and high densities of heterotrophic bacteria due to the biochemical degradation process (Mulling et al., 2014). Hence, further treatment is necessary if secondary effluent is to replenish

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surface water. Otherwise, it can contaminate the receiving waters by causing eutrophication, oxygen depletion and other adverse effects, especially for those that has been polluted heavily to some extent.

As a rapid-growing and compelling ecological restoration technology, constructed wetlands (CWs) would be an ideal alternative for dealing with the above problem. CWs have found many applications in treating municipal (Vymazal, 2005; Chung et al., 2008), industrial (Türker et al., 2013; DiMuro et al., 2014) and agricultural (Maucieri et al., 2014) wastewaters, as well as polluted surface water (Jia et al., 2014) and runoff (Beutel et al., 2014; Gill et al., 2014). It is difficult for a single-stage wetland system to treat wastewater from various sources (Zhang et al., 2009). Pollutants in a wetland are removed via a complex variety of physical, chemical and biological processes for which conditions required are, in certain cases, conflicting (Saeed and Sun, 2011). For example, total nitrogen (TN) is typically removed from wastewater primarily via the classic biodegradation route, i.e., ammonification, autotrophic nitrification, followed by heterotrophic denitrification (Saeed and Sun, 2011). Nitrification is a biological oxidation process, whereas denitrification occurs only under anaerobic or anoxic conditions (Vymazal, 2007). Consequently, single-stage CWs cannot achieve high removal of TN due to their inability to provide both aerobic and anaerobic conditions simultaneously (Vymazal, 2007). Hence, more and more attention is being paid to hybrid wetland systems, which combine different types of CWs or other wastewater treatment methods, such as oxidation ponds, to complement each other, and the hybrid systems have proven to be more effective in removing pollutants (Vymazal, 2005, 2013; Zhai et al., 2006; Ávila et al., 2013; Jia et al., 2014; Wang et al., 2014). Moreover, some other methods, such as artificial aeration, are also adopted to enhance the treatment effects (Ouellet-Plamondon et al., 2006; Dong et al., 2012). However, few studies refer to the employment of CWs to polish secondary effluent and purify runoff simultaneously prior to replenishment of surface water.

Due to such a lack of knowledge, lab-scale combined oxidation pond-constructed wetland (OP-CW) ecosystems treating the composite wastewater were established in this study to investigate the factors that affect the system performance. A number of factors, such as the plant species, temperature, organic carbon source, hydraulic residence time (HRT), dissolved oxygen (DO) and substrate characteristics, would affect the treatment efficiency of the system (Akratos and Tsihrintzis, 2007; Kotti et al., 2010). Therefore, multifactor orthogonal experiment was designed to investigate the influence of the tested factors and determine the optimal operating conditions for the system. The specific objectives of this study were to (1) select and explain the factors mostly influencing the system performance by employing multifactor orthogonal experiment, and (2) identify the optimal operating conditions to optimize the operation of the system.

2. Methods

2.1. Orthogonal experiment design

Denitrification is strongly dependent on carbon quantity and quality in most CWs (Wen et al., 2010). However, most of the organics in the secondary effluent are refractory, which is very detrimental for TN removal, and the same problem exists for runoff with the measured B/C being 0.1–0.15. B/C is the ratio of five-day biochemical oxygen demand (BOD_5) to chemical oxygen demand (COD_{Cr}), indicating the difficult degree of biodegradation of organic pollutants in the wastewater. Generally, the wastewater is not suitable for being biodegraded when B/C < 0.25, is difficult to be biodegraded when 0.25 < B/C < 0.30, is biodegradable when 0.30 < B/C < 0.45, and is readily biodegraded when B/C > 0.45. Owing to the relatively intact ecosystems and self-purification function, there is a considerable amount of biodegradable organics in surface water. Accordingly, mixing surface water with secondary effluent and runoff would improve the biodegradability of influent and thus favor the removal of TN. Moreover, surface water could also be purified, and the operating costs would be further reduced without adding external carbon sources. Therefore, the B/C value of the influent, which can be controlled by regulating the volume ratios of different water sources in the influent, should be considered as an important influencing factor. The impact of aeration intensity and period on the treatment efficiency of CWs is well documented (Ouellet-Plamondon et al., 2006; Dong et al., 2012; Zapater-Pereyra et al., 2014). However, little information on the aeration position, which may have a significant impact on the distribution of DO concentration and thus the removal of pollutants by influencing oxygen diffusion paths, is available from the literature. Thus, the effects of aeration intensity and aeration position were both investigated in this study. As a common and important factor, HRT was also taken into account. Four levels were taken for each factor. For the factor of B/C, the treatment levels were set to approximately 0.20, 0.25, 0.30 and 0.35 according to the biodegradability of wastewater indicated by B/C value. For aeration intensity (expressed as air/water ratio), the levels were set to 2:1, 3:1, 4:1 and 6:1 after testing the DO concentrations near the site of aeration in the starting stage of the experiment. The aeration position was arranged at the bottom, lower-middle part, middle-upper part and surface of the CW columns in different treatment systems. The levels of HRT in the CW columns were set to 1, 1.5, 2 and 2.5 d according to the empirical value. Moreover, a continuous aeration mode was adopted in this study.

In conventional full factorial experiments involving four factors with four levels, the total number of experiments required to run is $4^4 = 256$, which can be reduced to 16 by multifactor orthogonal experiment. The orthogonal design can cover a wide range of operating conditions with much fewer experiments, greatly decreasing the time required and reducing the cost. Moreover, in this study, the change of the influent turbidity would hardly affect the removal of organics, nitrogen and phosphorus due to the relatively low turbidity value (2.77–16.90 NTU in influent, Table 2). Therefore, the interaction between different pollutants mainly refers to the effect of degradable organics on the nitrogen removal, which would be investigated through analyzing the effect of B/C value on NH_4^+-N and TN removal. Hence, L_{16} (4^4) orthogonal experiment was applied in this study with the assumption that no strong interaction effects existed among these four factors. Details of the factors and levels are provided in Table 1.

Experiments started in April 2014 and lasted for 28 weeks. The recorded lowest (24.9 °C) and highest (32 °C) temperatures were in April and July, respectively. Given that there were no large fluctuations in temperature, the effect of temperature on the system performance was not discussed in this study.

2.2. Influent

The composite wastewater influent contained secondary effluent and surface water on dry days, and secondary effluent, surface water and runoff on rainy days. The secondary effluent and surface water were, respectively, collected from a municipal WWTP in Tianjin, North China, and the Youyi Lake of Tianjin University. The main sewage treatment process in the WWTP is Anaerobic–Anoxic–Oxic (A/A/O) process. Given that the first flush is heavily contaminated, the initial runoff should be discarded before discharge into the treatment system. Synthetic runoff similar to that of Tianjin, China, after splitting 3–4 mm rainfall in pollutant concentrations in terms of COD_{Cr}, ammonia (NH_4^+-N), TN and total