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Dynamics of nitrogen transformation depending on different operational strategies in laboratory-scale tidal flow constructed wetlands

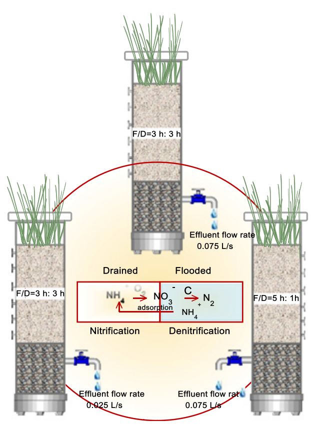
Yongjiang Chang [a], Shubiao Wu [b,*], Tao Zhang [c], Robert Mazur [d], Changle Pang [b], Renjie Dong [b]

[a] College of Agronomy and Biotechnology, China Agricultural University, Beijing 100193, PR China
[b] Key Laboratory of Clean Utilization Technology for Renewable Energy in Ministry of Agriculture, College of Engineering, China Agricultural University, 100083 Beijing, PR China
[c] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, PR China
[d] Department of Hydraulic and Sanitary Engineering, Faculty of Land Reclamation and Environmental Engineering, Poznan University of Life Sciences, Poland

HIGHLIGHTS

- Up to 90% of organic matter removal performance in TFCWs was achieved.
- 3 h drained and 1 h flooded time was identified to complete nitrification.
- Slow discharge flow developed better nitrification within TFCWs.
- TFCWs were shown to be a robust technology for high TN removal.
- No effect of operational strategies in TFCWs on P removal was obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of different flooded/drained (F/D) time ratios and different effluent flow rates on the dynamics of nitrogen transformations in three laboratory-scale tidal flow constructed wetland systems (TFCWs-A, B, and C) under varying NH_4^+-N and COD influent loadings was investigated in this study. Good organic matter removal performance up to 90% was achieved for all experimental TFCWs under inflow concentrations of 300 and 150 mg/L regardless of F/D and effluent flow rate. The ammonium removal efficiency of wetland with F/D = 3 h:3 h (55%) was higher than that of the wetland with F/D = 5 h:1 h (47%) under an ammonium inflow concentration of 60 mg/L, indicating the positive effect of longer drained and shorter flooded time on tidal-operated wetlands under nitrification. In addition, more uniform oxygen distribution and better nitrification capacity within the wetland might be achieved with a relatively slow effluent flow rate of 0.025 L/s. TFCWs were shown to be a robust and reliable option to achieve high TN removal of 70% due to its repeated cycle of "wet" and "dry" periods, particularly for the treatment of wastewater with high organic content. Moreover, F/D and effluent flow rates of tidal flow constructed wetlands exhibited no significant effect on phosphorus removal in this study. Other techniques, such as pretreatment or post treatment, require further investigation.

* Corresponding author. Tel.: +86 10 62737852; fax: +86 10 62737885.
E-mail address: wushubiao@gmail.com (S. Wu).

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1. Introduction

Constructed wetlands (CWs) are considered as a promising wastewater treatment technology and have been widely applied for the treatment of various wastewaters in many countries for their advantages of low operating cost, good efficiency, and easy maintenance (Albuquerque et al., 2009; Greenway, 2005; Haberl et al., 2003; Kadlec and Wallace, 2008; Williams, 2002).

The process of nitrogen removal in CWs is extremely complex and includes ammonia volatilization, plant and microbial uptake, adsorption, nitrification, denitrification, and anaerobic ammonia oxidation (ANAMMOX), among others (Vymazal, 2007). Nevertheless, biological nitrification–denitrification is widely acknowledged to be the major nitrogen removal mechanism.

However, the nitrification process was recognized as a limiting step of total nitrogen (TN) removal because traditional CWs generally had limited oxygen supply capability (Stein and Hook, 2005; Wu et al., 2001). Horizontal subsurface flow CWs (HSSF CWs) and vertical flow CWs (VF CWs), as the most traditional types of wetlands, are intensively applied worldwide. However, the oxygen transfer rate of HSSF CWs is reported to only be approximately 1 $g/m^2 \cdot d$ to 8 $g/m^2 \cdot d$ because of the limited oxygen release from plants and atmospheric diffusion under long-term saturated conditions (Cooper, 2005; Hu et al., 2012b; Maltais-Landry et al., 2009). Compared with HSSF CWs, VF CWs were demonstrated to have higher oxygen transfer capability because of the wastewater vertical movement in unsaturated wetland beds (Cooper, 2005). The reported oxygen transfer rate in VF CWs is approximately 50 $g/m^2 \cdot d$ to 90 $g/m^2 \cdot d$, which still cannot fully meet the requirement for a large amount of oxygen for the microbial process of organic matter oxidation and nitrification, particularly for the treatment of high-strength wastewaters (Cooper et al., 1997; De Feo et al., 2005). Therefore, the enhancement of oxygen transfer capacity of CWs is crucial to enhance the nitrification process and further improve the removal efficiency of TN (Platzer, 1999).

For the improvement of oxygen supply in CW beds, a few intensified CWs were invented, such as artificial aerated CWs and tidal flow CWs (TFCWs). Artificial aerated CWs inject compressed air into the bed matrix by using a blower continuously or intermittently to enhance oxygen concentration in the wetlands (Fan et al., 2013b; Ouellet-Plamondon et al., 2006). Compared with traditional CWs, the removal efficiency of pollutants in aerated wetlands is certainly improved. However, considering the energy consumption of the aeration process and complex maintenance of aerators, the large-scale application of aerated wetlands remains limited, particularly in economically undeveloped areas (Austin and Nivala, 2009; Kadlec and Wallace, 2009).

TFCWs emerged as a relatively novel intensified CW system where the wetland matrix is rhythmically filled with wastewater and then drained. Through the repeated cycle of "wet" and "dry" periods, wastewater acts as a passive pump to repel and draw the oxygen from the atmosphere into the matrix. Thus, oxygen transfer is significantly enhanced (Hu et al., 2012a; Sun et al., 2005; Wu et al., 2011; Zhao et al., 2004). Compared with aerated wetlands, TFCWs have the advantage of requiring only half of the energy and area to treat the same volume of wastewater, which makes TFCWs a great potential for wastewater treatment (Austin and Nivala, 2009). Tidal operation strategy in wetlands has been proven to be an effective method to increase oxygen transfer rate up to be 450 $g/m^2 \cdot d$, significantly higher than in conventional CWs (Wu et al., 2011). Moreover, based on a calculation of oxygen supply and demand in tidal wetlands, the transformation of organic matter and ammonium in TFCWs was indicated to be performed mainly by aerobic processes (Wu et al., 2011). Recent insights in TFCWs indicate that aerobic processes (COD oxidation and nitrification) mainly occur during the bed drained periods. So the enhanced oxygen supply in TFCWs could probably due to the direct use of the atmospheric oxygen rather than the function of the "passive pump" (Hu et al., 2014). However, the successful oxygenation of TFCWs in the performance improvement of ammonium and organic matter removal, the anaerobic environment in TFCWs and the activity of denitrifiers were quite limited, causing an accumulation of nitrate in the effluent and low removal of TN (Hu et al., 2012b; Wu et al., 2011; Yang et al., 2011, 2012). Therefore, to enhance TN removal in TFCWs, further investigation of the mechanisms of nitrogen transformation depending on different tidal operational strategies is necessary.

The current guiding theory for nitrogen removal in TFCWs was proposed as a two-step theory, as reported by former studies (Austin, 2006; Tanner et al., 1999). First, ammonium cations (NH_4^+) are adsorbed on negatively charge surfaces when wetland cells are flooded. Second, as wetland cells drain, air is drawn into the media pore spaces immediately, and NH_4^+ ions are then rapidly nitrified under this condition (Austin et al., 2003; McBride and Tanner, 1999). In the next flood cycle, nitrate (NO_3^-) and nitrite (NO_2^-) anions desorb into bulk water, where they serve as terminal electron acceptors for denitrification, thus reducing NO_3^- into atmospheric nitrogen. Besides, simultaneous nitrification and denitrification could be substantial during the bed drained periods as well (Hu et al., 2014).

Based on the above, in TFCWs, different flooded/drained (F/D) time ratios and drainage negative pressure may affect nitrogen removal efficiency. Flooded periods influence the adsorption of NH_4^+ on the matrix surfaces and the process of denitrification. Drain period determines the nitrification capability in a wetland system. Moreover, the wetland oxygen transfer capacity and redox conditions were controlled by drainage negative pressure, which may be influenced by different effluent flow rates. In addition, the growth and spatial distribution of microbial community and bacterial population were influenced by F/D time ratio and drainage pressure, consequently affecting nitrogen removal efficiency. However, knowledge on the transformation of nitrogen pollutants and the mechanism of TN removal with different F/D time ratios and effluent flow rates remain insufficiently understood.

Therefore, this study aims to evaluate the influence of different F/D time ratios and different effluent flow rates on the dynamics of nitrogen transformation. Simultaneously, the effect of different influent NH_4^+-N and chemical oxygen demand (COD) loadings on the dynamics of nitrogen transformation was investigated. Moreover, phosphorus removal performance was also examined in three TFCWs under different operational strategies.

2. Materials and methods

2.1. Laboratory-scale wetlands

Three parallel laboratory-scale TFCWs (A, B, and C) were operated under different operating conditions. TFCW columns were constructed from a Perspex tube, each with a height of 150 cm and diameter of 18 cm. A 36 cm bottom layer of 1 cm to 3 cm diameter of washed river gravel with an average porosity value of 50%, which served as the drainage layer. The main filter layer of washed sand (particle size 0.45 mm to 3 mm) was filled to a depth of 92 cm with an average porosity value of 35%. Tidal operation was generated by a peristaltic pump and an automatic drain valve controlled by a timer (Fig. 1). The operating conditions of three TFCWs were summarized in Table 1. Wastewater was loaded to the three TFCWs in batch mode. After filling, three beds were kept flooded for different periods of time for evaluating the effect of F/D time ratio on TFCW performance. Then all the wastewater was drained out from three TFCWs by different effluent flow rates for the purpose of evaluating drainage negative pressure on TFCW performance.

TFCW-A and TFCW-B were set to have the same F/D time ratio of 3 h:3 h and different effluent flow rates of 0.075 and 0.025 L/s, respectively. The F/D time ratio of TFCW-C was set as F/D = 5 h:1 h, and the drainage flow rate of TFCW-C was the same as that of TFCW-A (0.075 L/s). The flood and drain cycle of three systems was set to occur at 6 h, and 4 cycles every day. Effluent was recycled to influent