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Review

The performance of the intensified constructed wetlands for organic matter and nitrogen removal: A review

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ABSTRACT

The effects of different aeration strategies including tidal flow (TF), effluent recirculation (ER) and artificial aeration (AA) on performance of vertical flow constructed wetland (VFCW), horizontal flow constructed wetland (HFCW) and hybrid constructed wetland (HCW) are comprehensively and critically reviewed in this paper. The removal efficiencies of nine types of intensified constructed wetlands (CWs) were examined in detail and their mean and standard deviation were estimated at 89 ± 11%, 84 ± 12%, 81 ± 17% and 63 ± 20% for total suspended solids (TSS), chemical oxygen demand (COD), ammonium-nitrogen (NH_4^+−N) and total nitrogen (TN), respectively. From the studied CWs, ER-HCW, TF-HCW, AA-VFCW and ER-VFCW emerged as the four best performing systems. The overall removal efficiency of TSS, COD, NH_4^+−N and TN by ER-HCW was 98 ± 2%, 85 ± 11%, 83 ± 15% and 73 ± 11%, respectively. Specifically, the ER enhances the interactions between pollutants and micro-organisms, consequently, the efficient removal of NH_4^+−N and TN has been achieved in ER-HCW. The TF has a positive effect in refreshing the wetland with fresh air to enhance the dissolved oxygen (DO) in the system. In case of AA, intermittent aeration is more effective than continuous aeration, as it facilitates the establishment of aerobic and anaerobic conditions suitable for nitrification and denitrification. Statistical analysis shows that DO, organic loading rate and specific surface area requirement are the most significant factors that influence the performance of intensified CWs.

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1. Introduction

The constructed wetlands (CWs) are a cost-effective option to treat wastewater. These are defined as man-made systems, which involve the growth of plants (e.g. duckweeds or common reeds) in a pond and the use of sunlight to produce oxygen, which is used by micro-organisms to break organic matter in the wastewater. This interaction of plants, microorganisms and soil leads to natural processes (physical, chemical and biological) that are used to remove pollutants from wastewater (Vymazal, 2005). Two designs of CWs are widely used: free water surface flow constructed wetland (FWSCW) and subsurface flow constructed wetland (SSFCW). Among the SSFCW two types exist: horizontal flow constructed wetland (HFCW) and vertical flow constructed wetland (VFCW). The CWs have many advantages such as they are simple in construction as well as in operation and maintenance, have high robustness and process stability, high buffer capacity for hydraulic and organic load fluctuations, and a low sludge production (Langergraber et al., 2010). Additionally they provide green areas and improve environmental quality. The performance and pollutant removal mechanisms of all types of CWs are different. A brief description of each system is presented, while further details can be found in Kadlec and Wallace (2009).

FWSCW consists of open water, floating vegetation and emergent plants. FWSCW has some limitations such as the water flows above the soil substrate limits its contact with the CW substrate and exposes the water to the environment. Due to the limitations of FWSCW, the SSFCW was developed. In HFCW wastewater stays below the surface of the media and flows horizontally through the bed until it reaches the outlet (Kadlec and Wallace, 2009). In HFCW the oxygen supply by the plants was overestimated and denitrification and anaerobic degradation of organic matter was achieved because the majority of the saturated bed was anaerobic (Vymazal, 2005). Later, VFCW was developed in which the beds are pulse-loaded with a large amount of water to temporarily flood the surface of the bed. The pulse-loading results in good oxygen transfer, consequently, VFCW is capable to nitrify as compared to HFCW (Cooper et al., 1996). VFCW is efficient in removal of organic matter and total suspended solids (TSS) but provide little denitrification compared to HFCW. Hence, removal of total nitrogen (TN) is limited in this system. Later, the idea of a hybrid constructed wetland (HCW), the combination of VFCW and HFCW one next to the other, was developed for the purpose of mainly nitrification-denitrification treatment trains to produce good quality effluent (Cooper et al., 1999). However, to achieve higher removal of TN other types of HCWs including FWSCW and multistage CWs have also been established (Vymazal, 2013).

The CWs as a wastewater treatment technology was started by Käthe Seidel in the 1960s and by Reinhold Kickuth in the 1970s (Kadlec and Wallace, 2009). At the primary stage of CWs development, they were mainly used for the tertiary and secondary treatment of domestic/municipal wastewater (Kivaisi, 2001). The CWs development has received great attention from both scientists and engineers in the last decades. These engineered systems have been successfully used to alleviate environmental pollution by removing a wide variety of pollutants from wastewater such as organic matter, suspended solids, pathogens, metals, and nutrients (Kadlec and Wallace, 2009). The application of CWs has been expanded to purify agricultural effluents (Sun et al., 2006), landfill leachates (Nivala et al., 2007), as well as industrial effluents (S. Wu et al., 2015a).

The removal of organic matter such as TSS, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) by conventional FWSCW was >70% (Kadlec and Wallace, 2009). The removal of TSS in HFCW and VFCW was <80% and >85%, respectively, the removal of BOD in HFCW and VFCW was >75% and 90%, respectively, whereas, COD removal in HFCW and VFCW was >65%. Nevertheless, HCW was found more effective for the removal of TSS, BOD and COD up to >90%, >85% and >85%, respectively (Zhang et al., 2014). In all types of CWs reported by Vymazal (2007), the removal of TN varied between 40 and 55% with removed load ranging between 250 and 630 g N m^{-2} yr^{-1} depending on CWs type and inflow loading. The removal of nitrogen via harvesting of aboveground biomass of emergent vegetation is low (100–200 g N m^{-2} yr^{-1}) but for lightly loaded systems it could be significant.

Despite much progress to enhance the efficiency of CWs, some limitations of all types of CWs still remain such as the poor nitrogen removal and oxygen transfer limitation. Redox manipulation with aeration strategies such as tidal flow (TF), effluent recirculation (ER) and artificial aeration (AA) improves dissolved oxygen (DO) level (Foladori et al., 2013; Zhong et al., 2015; S. Wu et al., 2015b). Many research studies show that if sufficient oxygen within the system is available it gives microorganisms the conditions to complete biodegradation and enhances the system efficiency for organic matter and nitrogen removal. Therefore, oxidation-reduction potential (ORP) is the essential parameter in evaluation of oxic conditions in CWs, whereas, DO is considered one of the most important factors for organic matter and nitrogen removal.

Moreover, some other intensification methods have been used to enhance the removal of nitrogen such as: (1) partial saturation by external carbon source to increase denitrification (e.g. Laber et al., 1997; Lienard et al., 1998; Sirivedhin and Gray, 2006; Songliu et al., 2009; Langergraber et al., 2010); (2) the use of reactive media for intensification of wetlands to increase NH_4^+–N removal such as calcite (e.g. Seo et al., 2008) and zeolite (e.g. Canga et al., 2011; Wen et al., 2012; Liu et al., 2014; Millot et al., 2016).

The profound knowledge published in international journals and books on the enhanced treatment performance of intensified CWs has increased spectacularly in recent years. However, the comprehensive and critical review of their performance is lacking, which limits the comparative assessment of a number of intensified systems applying different aeration methods and wetland types. Moreover, studies are needed to conduct a synthesis on the recent developments on intensification of CWs and draw informed conclusions on the performance potential of CW treatment technology. This paper attempts to fill these research and knowledge gaps by conducting a comprehensive and critical review of the intensified CWs. Nine CW systems are examined, which are a combination of three wetland types, namely, VFCW, HFCW and HCW, and with three different aeration strategies (TF, ER and AA). A detailed comparison of the performance of these CWs for removal of organic matter and nitrogen is presented. The studied performance indicators are TSS, COD, ammonium-nitrogen (NH_4^+–N) and TN removal. Moreover, in case of TF the effects of intermittent flood (IF) and continuous flood (CF) are analyzed. Similarly, in case of AA the effects of aeration position (AP) and aeration mode (AM) such as intermittent aeration (IA) and continuous aeration (CA) on NH_4^+–N and TN removal are evaluated. The role of redox manipulation for the establishment of suitable conditions for pollutants removal is also summarized.

2. Methodology

Research articles, research papers as well as reviewed papers and books were searched from various sources, such as Scopus, Google Scholar and individual journal websites, related to the performance of the intensified CWs for organic matter and nitrogen removal. The search resulted in accumulation of about 100 documents, which were further screened and used for the purpose of this research. Considering the main objective of this review paper,