Water Research 103 (2016) 92–100

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Effect of by-pass and effluent recirculation on nitrogen removal in hybrid constructed wetlands for domestic and industrial wastewater treatment

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ARTICLE INFO

Article history:
Received 30 April 2016
Received in revised form
9 July 2016
Accepted 11 July 2016
Available online 13 July 2016

Keywords:
Hybrid constructed wetlands
Nitrogen removal rate
Step feeding
Effluent recirculation
Domestic and industrial wastewater

ABSTRACT

Hybrid constructed wetlands (CWs) including subsurface horizontal flow (HF) and vertical flow (VF) steps look for effective nitrification and denitrification through the combination of anaerobic/anoxic and aerobic conditions. Several CW configurations including several configurations of single pass systems (HF + HF, VF + VF, VF + HF), the Bp(VF + HF) arrangement (with feeding by-pass) and the R(HF + VF) system (with effluent recirculation) were tested treating synthetic domestic wastewater. Two HF/VF area ratios (AR) were tested for the VF + HF and Bp(VF + HF) systems. In addition, a R(VF + VF) system was tested for the treatment of a high strength industrial wastewater. The percentage removal of TSS, COD and BOD_5 was usually higher than 95% in all systems. The single pass systems showed TN removal below the threshold of 50% and low removal rates (0.6–1.2 g TN/m^2 d), except the VF + VF system which reached 63% and 3.5 g TN/m^2 d removal but only at high loading rates. Bp(VF + HF) systems required by-pass ratios of 40–50% and increased TN removal rates to approximately 50–60% in a sustainable manner. Removal rates depended on the AR value, increasing from 1.6 (AR 2.0) to 5.2 g TN/m^2 d (AR 0.5), both working with synthetic domestic wastewater. On real domestic wastewater the Bp (VF + HF) (AR 0.5 and 30% by-pass) reached 2.5 g TN/m^2 d removal rate. Effluent recirculation significantly improved the TN removal efficiency and rate. The R(HF + VF) system showed stable TN removals of approximately 80% at loading rates ranging from 2 to 8 g TN/m^2 d. High TN removal rates (up to 73% TN and 8.4 g TN/m^2 d) were also obtained for the R(VF + VF) system treating industrial wastewater.

1. Introduction

Constructed wetlands (CWs) have been established as an alternative to technical wastewater treatment systems for the sanitation of small communities, but single stage CWs are not able to get the more stringent discharge limits for nitrogen. Vertical flow (VF) CWs have predominant aerobic conditions, while the subsurface horizontal flow (HF) CWs mainly presented anaerobic conditions. Combining both types of CWs in hybrid systems could achieve complete nitrogen removal so, in the later years the interest in the study of multi-step and hybrid systems has increased (Ávila et al., 2013; Vymazal, 2013; Vymazal and Kröpfelová, 2015).

Vymazal (2013) surveyed 60 hybrid constructed wetlands from 24 countries reported since 2003 to 2012. The most commonly used hybrid system is a VF + HF constructed wetland which has been used for treatment of both sewage and industrial wastewaters. On the other hand, the use of a HF + VF system has been reported only for treatment of municipal sewage. The free water system (FWS) is also used in several hybrid configurations. Vymazal (2013) found that the VF + HF configuration was slightly more efficient in ammonia removal than other hybrid configurations, including HF + VF systems. All types of hybrid CWs are comparable with single VF CWs in terms of NH_3-N removal rates whilst they are more efficient in total nitrogen removal than single HF or VF CWs (Vymazal, 2013). Furthermore, several kinds of industrial wastewaters have been treated in hybrid systems consisting of three (i.e. VF + VF + HF and VF + HF + VF) or more (VF + VF + HF + VF and VF + VF + VF + HF + VF) steps. Some of these multi-step systems directly treated high strength wastewaters such as slaughterhouse (chemical oxygen demand (COD) of 3188 mg/L), milk parlour (up to 5000 mg COD/L), potato starch (24,017 mg COD/L) or tannery (11,500 mg COD/L) wastewaters.

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http://dx.doi.org/10.1016/j.watres.2016.07.028
0043-1354/

Focussing on surface removal rate (SRR) of total nitrogen (TN), Vymazal (2013) did not find significant difference neither in NH_3-N removal among the various types of hybrid systems which showed mean values ranging from 2.1 to 2.5 g NH_3-N/m^2 d, nor in TN removal (from 2.3 to 4.3 g TN/m^2 d). The highly variable design and operational conditions of the reviewed systems could be an explanation for the lack of significant differences in nitrogen removal among the hybrid systems. Besides the type of wastewater, environmental conditions, influent concentration and loading rates, the surface area ratio of saturated (i.e. HF units) to unsaturated units (mainly VF units) varied largely. For example, the two step VF + HF and HF + VF systems presented mean HF/VF area ratios (AR) of 2.7 (0.5–7.6) and 1.6 (0.9–3.1), respectively. Early VF + HF hybrid systems presented an even higher AR (Gaboutloeloe et al., 2009). Only some multi-step systems treating high strength wastewater were designed with low ARs ranging from 0.1 to 1.2 (Vymazal, 2013).

Recently, more sophisticated process designs were proposed in order to improve nitrogen removal and to increase the applied loads reducing the land area requirement. Tanner et al. (2012) pointed out that the endogenous organic carbon supply from plant biomass decay and root-zone exudation has often been found to be insufficient to achieve full denitrification in VF + HF hybrid systems. These authors (Tanner et al., 2012) proved the use of carbonaceous bioreactors which incorporate a slow-release source of organic C (e.g. wood chips) aiming to increase denitrification. Multi-feeding or by-pass of untreated influent to the second HF CW unit has also been reported (Stefanakis et al., 2011; Hu et al., 2012; Wang et al., 2014). Recirculation has been employed in various configurations (Brix et al., 2003; Brix and Arias, 2005; Ayaz et al., 2012; Foladori et al., 2013; Vázquez et al., 2013) in order to increase simultaneous nitrification and denitrification processes in either a single CW unit or in the two-step HF + VF systems. Artificial aeration in hydraulic saturated units, attaining to only part of the system or timed has been also considered (Pascual et al., 2016).

The objectives of this research are to compare the performance of various multi-step CW system configurations operating in the same conditions. Several configurations of single pass two-step systems (HF + HF, VF + VF, VF + HF), the VF + HF arrangement with feeding by-pass (Bp(VF + HF)), and the HF + VF system with effluent recirculation (R(HF + VF)) were tested on synthetic domestic wastewater for organic matter, ammonia and TN removal. Two alternatives of the VF + HF (with and without step-feeding) configuration, varying the relative surface area of each unit, were studied. Finally, the VF + VF system with effluent recirculation (R(VF + VF)) was tested for the treatment of a high strength influent simulating food industry wastewater.

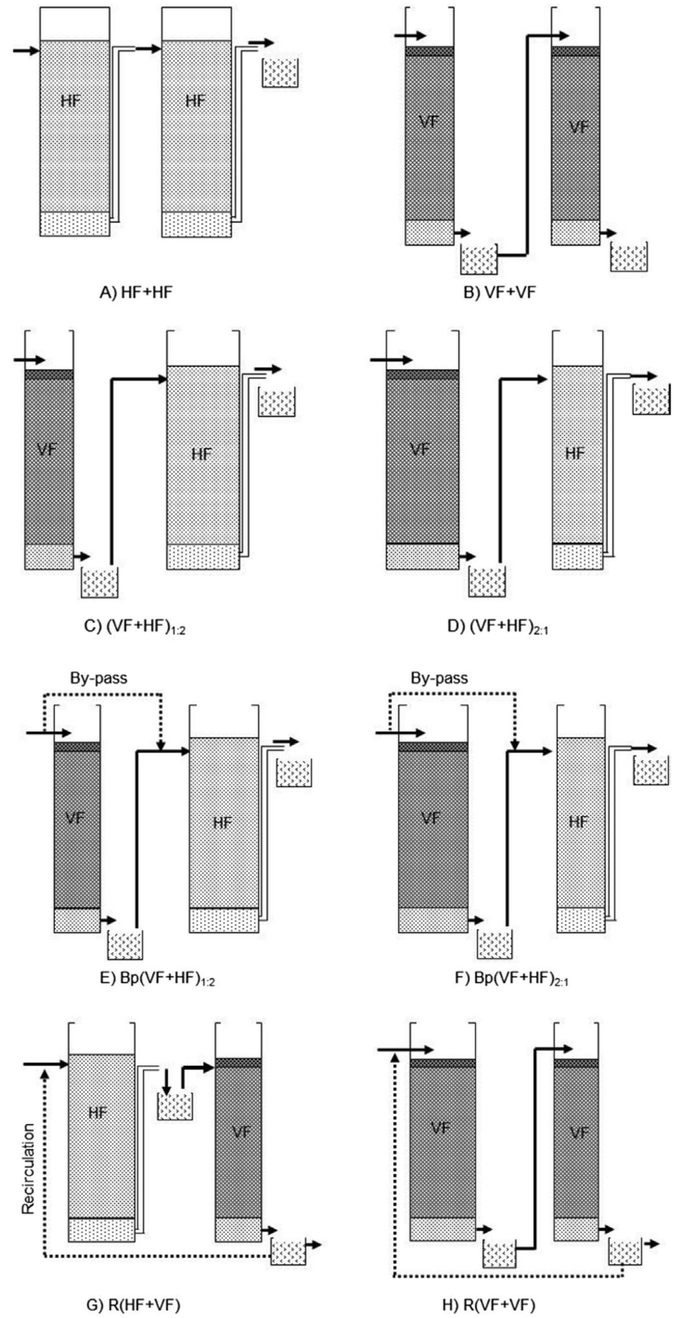

Fig. 1. Schemes of the lab-scale systems: A) Single pass HF + HF system, B) Single pass VF + VF system, C) and D) Single pass hybrid VF + HF systems with different relative surface areas, E) and F) Hybrid VF + HF HF + VF system with effluent recirculation, H) Two-step VF + VF system with effluent recirculation. The first step:second step surface area ratios are 1:1 (A,B), 1:2 (C,E), and 2:1 (D,F,G,H).

2. Materials and methods

2.1. Lab-scale hybrid systems

The schemes of the eight two-step lab systems are shown in Fig. 1. Unsaturated VF CWs were simulated by lab-scale columns, as proposed by Andreottola et al. (2007). Similar cylindrical columns were adapted to simulate subsurface horizontal flow (HF) CWs by applying conditions of continuous hydraulic saturation. Thus, HF columns were similar to VF columns and were also operated in down-flow mode, but changing the conditions required to simulate actual HF CWs, such as hydraulic saturation conditions, continuous flow, bed particle size and influent point below the gravel surface. Both VF and HF columns were made of methacrylate with two optional internal diameters of 10 and 14 cm and a total height of 60 cm. The column cross-sectional areas were used to calculate the hydraulic loading rate (HLR) and the surface loading rate (SLR) for both the VF and HF CWs. Overall HLR was calculated as the influent flow divided by the surface area of both units whilst the SLR was calculated as the product of HLR by the concentration. In this way, effluent recirculation (if the case) did not affected the values of HLR and SLR.

The HF bed consisted of a 10 cm drainage layer of 10–20 mm gravel at the bottom, and a 40 cm filtering layer of 6–12 mm fine gravel (porosity 40%), the influent entering the column 3 cm below the gravel surface. The wastewater flowed downwards until reach the drainage layer and went out upwards through a pipe until reach the water level in the column. This disposition created continuous