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Recirculation or artificial aeration in vertical flow constructed wetlands: A comparative study for treating high load wastewater

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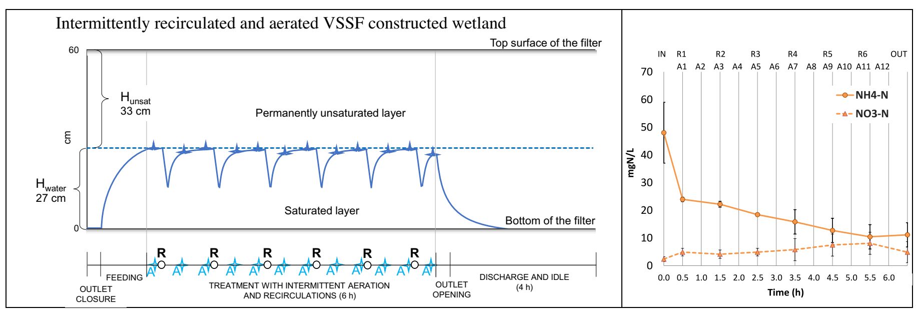
HIGHLIGHTS

- Recirculation and aeration applied in vertical subsurface flow constructed wetlands.
- High removal of COD, TKN, and TN, especially in the aerated and recirculated system.
- Simultaneous nitrification/denitrification in the aerated and recirculated wetland.
- The surface area requirement could be reduced from 3.6 to 1.5 m^2/person equivalent.

GRAPHICAL ABSTRACT



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ABSTRACT

Vertical subsurface-flow constructed wetlands at pilot-scale have been applied to treat high hydraulic and organic loads by implementing the following configurations: (1) intermittent recirculation of the treated wastewater from the bottom to the top of the bed, (2) intermittent artificial aeration supplied at the bottom of the bed and (3) the combination of both. These configurations were operated with a saturated bottom layer for a 6 h-treatment phase, followed by a free drainage phase prior to a new feeding. COD removal efficiency was 85–90% in all the configurations and removed loads were 54–70 gCOD m^{-2} d^{-1}. The aerated and recirculated wetland resulted in a higher total nitrogen removal (8.6 gN m^{-2} d^{-1}) due to simultaneous nitrification/denitrification, even in the presence of intermittent aeration (6.8 Nm^3 m^{-2} d^{-1}). The extra investment needed for implementing aeration/recirculation would be compensated for by a reduction of the surface area per population equivalent, which decreased to 1.5 m^2/PE.

1. Introduction

In the application of horizontal subsurface flow constructed wetlands (HSSF) or vertical subsurface flow constructed wetlands (VSSF) in the treatment of domestic or industrial wastewater, the land area requirement is the main constraint in some contexts, especially in mountainous areas. The possibility of applying high loads in constructed wetlands, especially to treat peaks in some periods (due to seasonal industries or tourism), would allow for the reduction of the surface area requirement, thus allowing the constructed wetlands to be more widely used in cases with limited space availability (Foladori et al., 2012). However, further research is needed to understand the performances of constructed wetlands under high applied loads with the aim of reducing surface areas and their footprints. Configurations that may include recirculation of wastewater or artificial aeration are currently being tested in research (*inter alia* Arias et al., 2005; Lavrova and Koumanova, 2010; Hu et al., 2012; Zhu et al., 2013) in order to increase the applied loads or to enhance the treatment performances, especially regarding nitrogen removal.

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Recirculation has been proposed in hybrid systems (HSSF + VSSF) to improve nitrogen removal performances, by pumping the nitrified VSSF effluent to a previous HSSF stage aimed at performing the removal of organic matter and supporting denitrification (Tunçsiper, 2009; Ayaz et al., 2012). In other studies, recirculation has been applied in VSSF systems treating pre-settled wastewater, by recirculating a fraction of the nitrified VSSF effluent to the septic tank where denitrification occurs due to biodegradable COD availability (Brix and Johansen, 2004; Brix and Arias, 2005; ÖNORM B 2505, 2008). Recirculation has been used on a single stage of a classical French VSSF to improve nitrification efficiency and to increase the removal of organics and suspended solids (Prost-Boucle and Molle, 2012). In a 4-stage tidal flow reed bed system (similar to fill-and-drain VSSFs), the final effluent was recirculated to the first stage to treat high strength wastewater (Zhao et al., 2004). A recirculating vertical flow constructed wetland, called RVFCW, has been developed for single houses (Gross et al., 2007; Sklarz et al., 2009), where the wastewater trickles through the bed into a reservoir and then is recirculated back to the top of the bed, with the aim of prolonging the contact time in the system and of enhancing oxygen diffusion during the trickling of wastewater through the bed.

Artificial aeration has been employed in many studies to enhance the removal performances in HSSF systems, which suffer from limited oxygen diffusion (Ouellet-Plamondon et al., 2006; Nivala et al., 2007; Maltais-Landry et al., 2009a,b; Zhang et al., 2010; Butterworth et al., 2013; Fan et al., 2013a).

Conversely, very little research focuses on the application of artificial aeration in fill-and-drain VSSF systems because, in these systems, a natural and spontaneous permeation of air is permitted by the sequence of filling and draining (Green et al., 1998). However, when high loads are applied, the amount of oxygen supplied by natural aeration could be insufficient to ensure both the oxidation of organic matter and nitrification due to the high levels of oxygen demand (*inter alia* Vymazal, 2007; Hu et al., 2012; Fan et al., 2013b). In this case, artificial aeration could enhance the oxygen availability in the VSSF systems (Dong et al., 2012; Tang et al., 2008; Ong et al., 2010; Pan et al., 2012; Fan et al., 2013b). In particular, intermittent aeration has been recently proven to be an effective way of improving not only nitrification but also total nitrogen removal, due to the alternation of aerobic and anaerobic phases (Jia et al., 2010; Fan et al., 2013b) and the formation of microaerobic/anaerobic zones (Dong et al., 2012). Moreover, intermittent aeration could save operational costs in respect to continuous aeration (Liu et al., 2013).

Despite this recent increased interest in recirculated or aerated VSSF systems, this specific topic has never been completely investigated and most of the applications remain at the lab-scale using synthetic wastewater.

In this research, VSSF configurations equipped either with recirculation and/or artificial aeration were investigated and compared at pilot-scale in the treatment of real domestic wastewater at high loads (for both organics and nitrogen) in an attempt to reduce the specific surface area per population equivalent (PE). A saturated layer was formed on the bottom of the VSSF with the intention of prolonging the hydraulic retention time of the wastewater, as the efficiency of pollution removal in constructed wetlands depends greatly upon retention time (Toet et al., 2005). There has been no reported research in the literature comparing recirculated and/or aerated VSSF systems (with a saturated layer on the bottom) for the treatment of real wastewater at high loads.

The recirculated and/or aerated VSSF systems were compared with a conventional down-flow VSSF (designed following local guidelines), monitored in parallel and then used as a control. Local guidelines indicate effluent concentrations of 125 mgCOD/L, 35 mgTSS/L, whilst requirements are not so strict in regard to nitrification and total N removal (nitrification efficiency of 70% or higher and removal percentage of total N around 70% are suitable). These limits can be commonly obtained in a hybrid configuration (VSSF + HSSF), where HSSF has a polishing role.

2. Methods

2.1. VSSF pilot plant

The outdoor VSSF pilot plant, located in the Alps (Ranzo, Province of Trento, Italy) at 739 m a.s.l., treated real domestic wastewater. The scheme of the pilot plant has been described previously (Foladori et al., 2012). The raw wastewater passed through a mechanical grid and an Imhoff tank before entering the pilot plant consisting of two parallel lines (Fig. 1):

(1) A conventional down-flow VSSF (surface area: 2.25 m^2; depth: 0.8 m) designed with a specific surface area of 3.6 m^2/PE in compliance with local guidelines; this line was used as a control and afterwards labeled C-VSSF. The filling materials (starting from the bottom) were as follows: a drainage layer of 0.2 m gravel Ø15–30 mm (porosity, $p = 31\%$), a transition layer of 0.05 m gravel Ø7–15 mm ($p = 30\%$), a main layer of 0.5 m sand Ø1–3 mm ($p = 31\%$) and a top layer of 0.05 m gravel Ø7–15 mm ($p = 30\%$);

(2) A high-load VSSF line (surface area: 2.25 m^2; depth: 0.6 m) with a specific surface area of 1.4–1.8 m^2/PE, dictated by the configuration used; in this line, intermittent recirculation, intermittent artificial aeration and a combination of both were applied consecutively (see Section 2.2). The filling materials (starting from the bottom) were as follows: a drainage layer of 0.2 m gravel Ø15–30 mm ($p = 31\%$), a transition layer of 0.1 m gravel Ø7–15 mm ($p = 30\%$), a main layer of 0.3 m sand Ø1–6 mm ($p = 30\%$).

The saturated hydraulic conductivity measured for the main layer was around 6×10^{-2} cm/s in both the VSSF systems.

2.2. VSSF configurations tested in the pilot plant

The C-VSSF, used as a control line, was operated as a conventional down-flow VSSF with a single feeding per cycle applied on top of the bed (6.6 h/cycle, 3.6 cycles/day on average), the wastewater being discharged by free drainage for the entire cycle.

The high-load VSSF configurations were tested, subsequently applied (10.5 h/cycle, 2.3 cycles/day on average) and then compared with the control C-VSSF. In these three configurations, the wastewater was fed on top of the bed at the beginning of the cycle. The outlet was controlled by an automated valve placed on the bottom of the VSSF bed. Just before feeding, the automated discharge valve was closed to maintain saturated conditions in the bottom layers for 6 h/cycle (treatment phase).

(1) *High-load VSSF with intermittent recirculation* (R-VSSF): The R-VSSF was equipped with a small pump providing a flow rate of 0.56 $m^3\ m^{-2}\ h^{-1}$ and pipes for the wastewater that was recirculated from the bottom to the top of the filter for 5 min every hour during the treatment phase (a total of 6 intermittent recirculations per cycle). The recirculation flow ratio (recirculated volume/influent volume) was 0.6/1.0 for each step. The result of the intermittent recirculation was a fluctuating water level in the bottom layer during the treatment phase (Fig. 2). At the end of the treatment phase, the valve was opened and the bed was drained for 4 h, restoring the unsaturated conditions and the permeation of air. The specific surface area was 1.4 m^2/PE on average.