

Multistage hybrid constructed wetland for enhanced removal of nitrogen

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ARTICLE INFO

Article history:

Received 4 January 2015

Received in revised form 13 July 2015

Accepted 4 September 2015

Available online 22 September 2015

Keywords:

Nitrogen

Common reed

Hybrid constructed wetland

Organics

Vertical flow

Horizontal flow

ABSTRACT

Hybrid constructed wetlands (HCWs) are very efficient in removal of total nitrogen. So far hybrid-constructed wetlands have been composed of various combinations of wetland units but most common combination is vertical flow–horizontal flow system. Also, multistage HCWs have recently been used. The present study describes the use of three-stage HCWs for treatment of municipal sewage. The system consists of saturated vertical flow, free-drain vertical and horizontal flow units in series. The experimental system with a total surface area of 10.1 m² has been operated for 19 months between March 2009 and October 2010. The results proved that multistage hybrid constructed wetland was able to remove efficiently organics, suspended solids and nitrogen. The overall removal efficiency amounted to 92.5%, 83.8%, 96.0%, 88.8% and 79.9% for BOD₅, COD, TSS, NH₄-N and TN, respectively. The aerobic vertical flow stage provided high degree of nitrification (removal rate of 4.17 g NH₄-N m⁻² d⁻¹) while remaining anaerobic stages (first and third) provided suitable conditions for denitrification (removal rates of 0.83 g N-NO₃ m⁻² d⁻¹ and 0.47 g N-NO₃ m⁻² d⁻¹, respectively). The outflow NH₄-N concentrations were below 5 mg l⁻¹ throughout the monitored period including winter period when the air temperature dropped below –20 °C. Plant biomass sequestered 28% and 26% of phosphorus and nitrogen inflow load, respectively.

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1. Introduction

Hybrid constructed wetlands (HCWs) have been developed in order to enhance the treatment efficiency of a single unit constructed wetland (Vymazal, 2013). In hybrid-constructed wetlands, the advantages of various systems can be combined to complement each other. Horizontal flows (HFCWs) are predominantly anoxic/anaerobic and, therefore they provide suitable conditions for denitrification if nitrate is present. On the other hand, nitrification is very much limited by the lack of oxygen in water-saturated filtration bed and, therefore, removal of ammonia is usually very low. Vertical flow constructed wetlands (VFCWs), which are intermittently fed and thus aerobic, provide suitable for conditions for nitrification but denitrification does not take place in this system (Vymazal, 2007).

Hybrid constructed wetlands which combined VF and HF CWs in staged manner were first introduced by Seidel in Germany as early as in the 1960s (Seidel, 1965) but at that time these systems did not

spread too much. At present, hybrid constructed wetlands of various types are in operation in many countries worldwide (Vymazal, 2013). However, the most commonly used HCW is still VF–HF type (e.g., Öövel et al., 2007; Abidi et al., 2009; Comino et al., 2013; Zapater-Pereyra et al., 2015). This type of HCWs is predominantly used to treat domestic or municipal sewage (Vymazal, 2013) but examples of treatment of other types of wastewaters such as winery wastewaters (Serrano et al., 2011) cheese production wastewater (Comino et al., 2011) or landfill leachate (Bulc, 2006) have been documented as well. HCWs with combination HF–VF CWs, are used less frequently (Belmont et al., 2004; Singh et al., 2009) but if recirculation of nitrified outflow from a VF CW to the HF CW is carried out, removal of total nitrogen may be substantially enhanced (Ayaz et al., 2015).

At present, multistage HCWs are often used. The VF–VF–HF concept, originally developed by Seidel in the 1960s (Seidel, 1965), has been used, for example by ÓíHogain and Gray (2002) to treat municipal sewage in Ireland, Reeb and Werckmann (2005) for compost leachate in France, Sharma et al. (2013a,b) for high strength milking parlor wastewater in Japan or by Borin et al. (2013) and Mietto et al. (2015) to treat pig farm wastewater in Italy. Another multistage configuration of HCWs is a VH–HF–VF combination used by

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Table 1
Design parameters of the three-stage hybrid constructed wetland.

	1st stage	2nd stage	3rd stage
Area (m ²)	2.54	1.56 (1.3 × 1.2)	6.0 (8 × 0.75)
Shape	Circular	Rectangular	Rectangular
Depth (cm)	100 ^a	80 ^b	60 ^a
Plants	<i>Phragmites australis</i>	<i>P. australis</i>	<i>Phalaris arundinacea</i>
Filtration material	Crushed rock (4–8 mm, porosity 44%) Bottom 60 cm	Sand (1–4 mm, porosity 33%)	Crushed rock (4–8 mm)
	Crushed rock (16–32 mm, porosity 50%) Upper 40 cm		
Flow	Vertical, saturated ^a	Vertical, free drain	Horizontal subsurface

^a Water kept 5 cm below the surface with a standpipe.

^b Sand layer 70 cm, 5 cm gravel (4–8 mm) layers at the bottom and on the surface.

Seo et al. (2008) in Korea, Zupančič Justin et al. (2009) in Slovenia or Saeed et al. (2012) in Bangladesh. Many HCWs also include free water surface CWs (Liu et al., 2007; Brix et al., 2011; Xiong et al., 2011; Ávila et al., 2015). In recent years, combination of upflow and downflow VFCWs has been also used (Zhang et al., 2010, 2013; Zhao et al., 2011, 2013; Chang et al., 2012). Upflow VFCWs are water-saturated and more or less provide the same conditions as HF CWs. Langergraber et al. (2011) used a combination of two downflow VFCWs with saturated zone at the bottom of the first filter to allow for denitrification.

The present study reports on the performance of a HCW which combines saturated VFCW, free drain VFCW and HFCW. The design is unique in the use of saturated VF CW as the first stage and it was aimed primarily at the maximum removal of total nitrogen. The study presents the results from a 19-months period with continuous flow under steady conditions. The study is a follow up of the early experiments reported by Vymazal and Kröpfelová (2011).

2. Materials and methods

2.1. Experimental set-up

The experimental system was built at Třeboň Wastewater Treatment Plant (8000 PE), Czech Republic. The major features of the system were provided by Vymazal and Kröpfelová (2011) and are

shown in Table 1 and Supplemental Materials S1–S5. In brief, the system consisted of three stages of constructed wetlands (Fig. 1). The first one was operated as saturated vertical flow unit; the saturation was created by a standpipe which kept the water level about 5 cm below the filter surface. The second stage was a “typical” vertical flow unit with free drain and the last stage consisted of a horizontal subsurface flow unit. The vertical flow units were planted with Common reed (*Phragmites australis*), horizontal flow unit was planted with Reed canarygrass (*Phalaris arundinacea*) (Supplementary Material S6 and S7).

2.2. Hydraulic loading

Daily inflow of mechanically pretreated wastewater from Třeboň WWTP was divided into two 30-min batches and pumped at 8 AM and 8 PM. The average daily flow was originally designed at 250 l, but the flowmeter readings revealed that the exact average flow during the period March 12, 2009–June 12, 2010 was 246 l d^{−1}. For the last period of the experiment (May 1–October 12, 2010) the flow was increased to 510 l d^{−1}. The use of two 500 W pumps resulted in daily energy consumption of 1 kWh.

The recirculation was installed beyond the second wetland unit and water was returned to the first unit (Fig. 1) with recirculation rate of 100%, i.e. the outflow from the second vertical unit was split into two equal parts – one was pumped into the horizontal flow bed and one part was returned to the first vertical unit. This recirculation ratio was determined as optimal in the previous experiments (Vymazal and Kröpfelová, 2011). In the first period, the resulting hydraulic loading rates (HLR) for units 1, 2 and 3 were 18.1 cm d^{−1}, 29.5 cm d^{−1} and 3.8 cm d^{−1}, respectively, after the increase of the flow the respective HLRs increased to 37.5 cm d^{−1}, 61.1 cm d^{−1} and 7.9 cm d^{−1}.

2.3. Water quality, temperature, redox potential

The experiments were started on March 12, 2009 and were finished on October 12, 2010. Throughout the study, the samples were taken at 4 points:

- 1 inflow of mechanically pretreated wastewater to the anaerobic vertical flow wetland
- 2 outflow from the anaerobic filter (= inflow to free-drain wetland)
- 3 outflow from the free-drain vertical filter (= inflow to horizontal-flow wetland)
- 4 outflow from the horizontal flow wetland (final outflow)

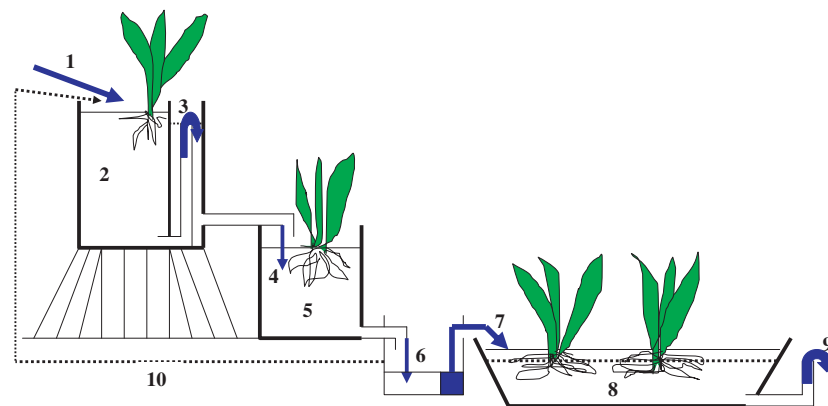


Fig. 1. Three-stage constructed wetland. 1 = inflow of mechanically pretreated municipal sewage, 2 = 1st stage, saturated vertical flow wetland, 3 = standpipe for water level regulation, 4 = outflow from the 1st stage, 5 = 2nd stage, free-drain vertical flow wetland, 6 = outflow from the 2nd stage, 7 = inflow to the 3rd stage, 8 = 3rd stage, horizontal flow wetland, 9 = final outflow, 10 = recirculation (Vymazal and Kröpfelová, 2011).

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