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Evaluation of the performance and space requirement by three different hybrid constructed wetlands in a stack arrangement

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ABSTRACT

Lack of space for a wastewater treatment plant is a common problem in many areas, especially in dense cities. Constructed wetlands (CWs) are efficient natural systems; however, they require large areas. The aim of this study is the development of a compact CW design for the treatment of domestic wastewater, the Duplex-CW: a hybrid system with a stacked design (vertical flow CW (VFCW) on top of a horizontal flow filter (HFF)). The performance of three different configurations of Duplex-CW, called fill and drain, stagnant batch and free drain, was compared. The VFCWs operated differently with the intention of creating different oxygen conditions, whereas the HFFs were operated identically. The Duplex-CWs were subjected to three different wastewater strengths, corresponding to designs of 7.9, 3.4 and 2.6 m^2 PE^{-1}. The highest strength was treated with and without artificial aeration of the VFCW of each configuration. The contribution to the total removal of each compartment (VFCW and HFF), the effects of the use of artificial aeration, the solids accumulation, above- and below-ground biomass and the footprint requirements of the three configurations tested were determined. The fill and drain configuration performed better than the other two, the VFCW compartment being more active in the treatment than the HFF. It achieved an area of 2.6–3.4 m^2 PE^{-1} and it needed 2–3 times lower area than what a single VFCW would have needed to reach similar total nitrogen effluent concentrations. The Duplex-CW did not contribute to the footprint reduction, for other parameters (e.g. COD, TSS and total phosphorus).
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1. Introduction

Constructed wetlands (CWs) are engineered to mimic natural wetlands and efficiently remove a wide range of pollutants (mainly organic matter) from wastewater. In certain situations, their usage is limited since they require large land areas to guarantee a good quality treatment (Kivaisi, 2001; Ghosh and Gopal, 2010; Foladori et al., 2013). This area can even be enlarged if different CW stages are necessary (Foladori et al., 2012), e.g., a first stage that provides aerobic conditions focusing on organic matter removal/nitrification and a second stage that provides anoxic conditions targeting denitrification. The CW space requirements can become a limiting factor for example in densely populated areas, in mountain regions and in situations when local authorities demand the treatment of wastewater before discharge.

Vertical flow CWs (VFCWs) are generally sized in Europe with 1–3 m^2 PE^{-1} (population equivalent) and horizontal flow CWs (HFCWs) with 5 m^2 PE^{-1} (Vymazal, 2011). The design depends on factors such as effluent needs, ambient temperatures, technology combinations and use of energy. If land area requirement is the main factor that decides the selection of a wastewater treatment system, other technologies such as activated sludge (0.2–0.4 m^2 PE^{-1}), trickling filters (0.3–0.7 m^2 PE^{-1}) or upflow anaerobic sludge blanket reactors (0.05–0.4 m^2 PE^{-1}) (von Sperling, 1996; Mburu et al., 2013) can become the foremost option. Since CW are natural treatment technologies that at the same time provide green areas, it is important to design CWs capable of appropriate wastewater treatment while assuring a smaller footprint.

Thus, this study aimed to develop a CW setup, called Duplex-CW, to be used when land availability is scarce. A Duplex-CW is a hybrid system that combines two compartments in a stacked design: a VFCW on top of a horizontal flow filter (HFF), similar to the system developed by Kantawanichkul et al. (2001). The specific design of the Duplex-CW is not defined and therefore the objectives of this research were: (i) to assess the differences among three different Duplex-CW configurations subjected to different domestic wastewater strengths, (ii) to select the most appropriate configuration for the Duplex-CW that can reduce the area requirements without deteriorating the effluent quality and

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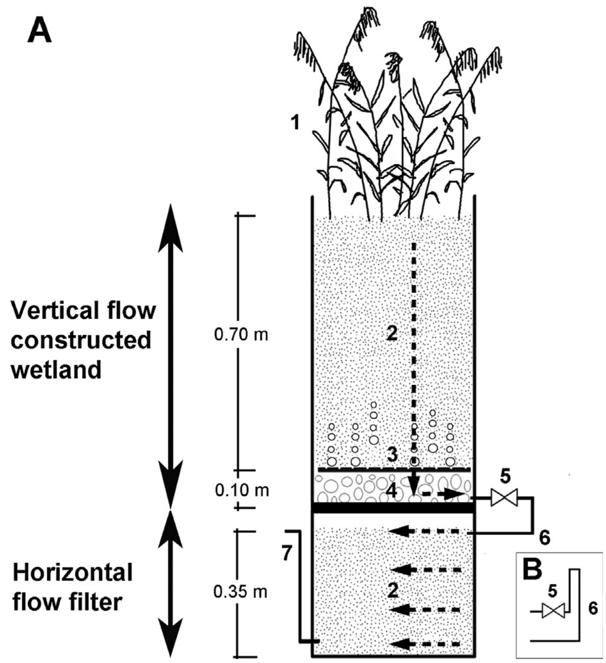

Fig. 1. Schematic representation of the Duplex-constructed wetland configurations (A) used in this study. (1) *P. australis*, (2) sand (support media), (3) aeration pipe, (4) gravel (drainage layer), (5) valve, (6) pipe connecting both compartments and (7) outlet pipe. The dashed line shows the path of the wastewater in the system. The graph on the bottom-right (B) represents the modification (elbow), done for the "Stagnant batch" configuration.

(iii) to evaluate the need of (intermittent) artificial aeration in the Duplex-CW design.

2. Materials and methods

2.1. Experimental set-up

Three laboratory scale Duplex-CWs, planted with *P. australis*, were evaluated in this study. The support medium was coarse sand (1–2 mm) and the drainage layer consisted of gravel (15–30 mm). Each Duplex-CW had a surface area of 0.24 m^2, while the depths were 0.80 m (0.70 m of sand and 0.10 m of drainage layer) for the VFCW and 0.35 m (only sand) for the HFF (Fig. 1). To provide artificial (active) aeration to the VFCWs, perforated horizontal pipes were placed between the sand and gravel layer. The systems were operated in a greenhouse under controlled temperature (20–23 °C) and light intensity (85–100 μmol photons m^{-2} sec^{-1} for 16 h d^{-1}).

The wastewater was applied intermittently, with a peristaltic pump, on top of the VFCW by means of a pipe manifold, twice per week (three batches of 13 L each day, batch interval of 6 h) corresponding to a hydraulic loading rate (HLR) of ~0.046 m^3 m^{-2} d^{-1}. The wastewater used was primary effluent from Harnaschpolder domestic wastewater treatment plant (Delft, The Netherlands) that was allowed to settle for approximately 2 h before its use. The physical and chemical characteristics of the settled wastewater are given in Table 1. This wastewater was applied during a 2-months start-up/adaptation period (previous to the experiments).

The three configurations of the Duplex-CW were named fill and drain (Fill&D), stagnant batch (StagB) and free drain (FreeD), following the different functioning modes of their VFCWs (Fig. 2). In the Fill&D system, three batches of wastewater were added while the outlet valve was closed. After 1 d, the valve was opened and water drained into the HFF (Fig. 2A). In the StagB system, an elbow joint (17 cm height) was installed at the outlet of the VFCW to retain 1.25 batches (16.25 L) of wastewater (stagnant wastewater) (Fig. 2B). The time between two consecutive batches was ~6 h within a feeding day and 3–4 d between the last batch and the first batch of two consecutive feeding days, therefore the HRT in this configuration varied between 6 h and 4 d (Fig. 2B). In the FreeD system, the outlet (valve) of the VFCW was permanently open enabling the water to directly discharge to the HFF in ~1.5 h (Fig. 2C). The HFF of all configurations worked similarly and had a HRT of 3–4 d.

The variations in the operational characteristics of each VFCW were done with the intention of creating different oxygen conditions: (i) Fill&D, the resting period in between feeding days assured an aerobic bed that facilitated aerobic processes when the wastewater was introduced; (ii) StagB, the permanent saturated bottom layer (stagnant batch) and the unsaturated top layer kept within the VFCW, created both anoxic-anaerobic and aerobic zones, and (iii) FreeD, the wastewater trickling along the depth assured permanent aerobic conditions in the VFCW bed.

Table 1
Average composition of the primary settled domestic wastewater used in this study (n = 9).

Parameters	Unit	Mean ± standard deviation
pH	–	7.0 ± 0.1
Electrical conductivity	μS cm^{-1}	1271 ± 175.3
Dissolved oxygen	mg L^{-1}	1.0 ± 0.6
Chemical oxygen demand	mg L^{-1}	329 ± 87.2
Total suspended solids	mg L^{-1}	118 ± 21
NH_4^+-N	mg L^{-1}	43 ± 7.5
NO_3^--N	mg L^{-1}	0.1 ± 0.1
Total nitrogen	mg L^{-1}	47 ± 9.5
Total phosphorus	mg L^{-1}	9.0 ± 1.0

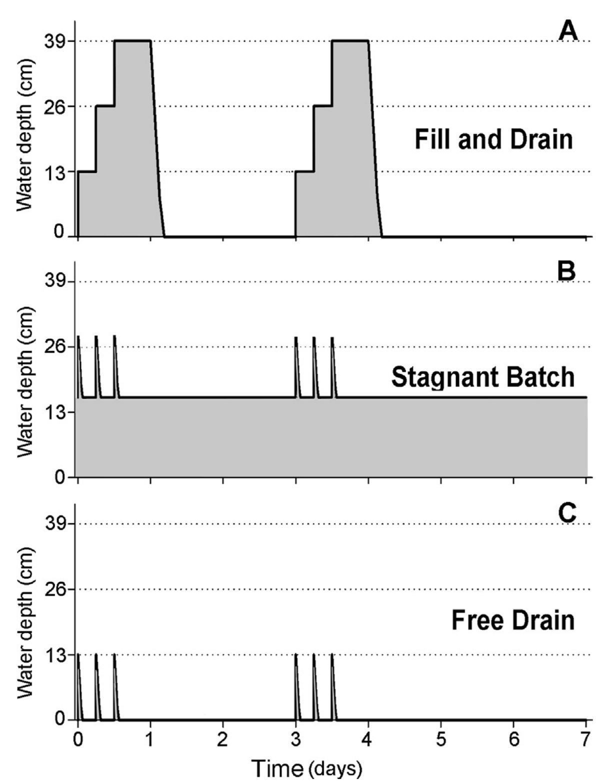

Fig. 2. Weekly hydraulic behaviour of the three vertical flow constructed wetlands (VFCWs) of each Duplex-CW configuration used in this study. Note: each batch of wastewater contained 13 L and had a depth of 13 cm in the VFCW.

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