Ecological Engineering 90 (2016) 203–214

Contents lists available at ScienceDirect

Ecological Engineering

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

Effect of plants and surface loading rate on the treatment efficiency of shallow subsurface constructed wetlands

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ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form
19 November 2015
Accepted 26 January 2016
Available online 13 February 2016

Keywords:
Wetland depth
Plant species
Biochemical oxygen demand
Nitrogen
Subsurface flow constructed wetlands

ABSTRACT

The aim of this research was to study the influence of the presence of plants and of plant species on the treatment efficiency of shallow (0.3 m effective depth) horizontal subsurface flow constructed wetlands (CWs) treating diluted municipal wastewater. The pilot plant was situated in A Coruña (Spain) and constituted of five CW units in parallel: CW1 (unplanted), CW2 (*Juncus effusus*) CW3 (*Iris pseudacorus*), CW4 (*Typha latifolia* L.) and CW5 (*Phragmites australis*). A long term study (from October 2009 to March 2012) was carried out with five monitoring campaigns during the two first years of operation at low surface loading rate (SLR, 2.5 g BOD_5/m^2 d on average) and two monitoring campaigns during the third year at design SLR (4.7 g BOD_5/m^2 d on average). At low SLR rate, significant differences between units were not found for TSS (89–93%), COD (83–88%) or BOD_5 (90–95%) percentage removal which, in turn, appeared at design SLR, when BOD_5 removal decreased to 78% (CW1), 69% (CW4), 87% (CW2), 86% (CW3) and 94% (CW5). Thus, the effect of plants on the removal efficiency of organic matter (COD, BOD_5) appeared to be dependent on the loading rate. CW2 reached the highest nitrogen removal, followed by CW4, CW5 and CW3 at a similar level and, finally, by CW1. Results indicate that the additional nitrogen removal rate in planted units increased with plant biomass productivity which also determined evapotranspiration variability between units. *Typha latifolia* L. appeared to be the most sensitive species to adverse conditions.

1. Introduction

Constructed wetlands (CWs) are engineered treatment systems for wastewater effluents up to 2000 habitant equivalents, showing a high sustainability potential when properly designed and maintained. Macrophytes play several roles in engineered ecosystems helping to stabilise the surface of the beds, provide good conditions for physical filtration and insulate the surface against coldness (Brix, 1997; Vymazal, 2011). Organic matter production and plant uptake of nutrients as well as root-zone oxygen and organic carbon release were identified as key factors influencing nutrient transformation and sequestration in low-loaded systems (Brix, 1997; Tanner, 2001; Vymazal, 2011). Studies showed that the above-ground and below-ground parts of the macrophytes increase microorganism diversity and provide large surface areas for the development of biofilm which is responsible for most of the microbial processes occurring in the wetlands (Button et al., 2015; Chen et al., 2014).

Most studies have shown that planted subsurface horizontal flow (HSSF) CWs achieve higher treatment efficiency than unplanted systems, at least for the removal of some pollutants. From a review carried out in 2001, Tanner (2001) concluded that wetland plants provide only small improvements in biological oxygen demand (BOD), chemical oxygen demand (COD) and faecal bacterial indicator removal but provide measurable enhancement of nutrient removal, mainly by promoting transformations to gaseous forms and sequestration in accumulating organic matter. This behaviour has been partially confirmed by recent studies that reported no significant differences between planted and unplanted systems in removing BOD and COD (Vacca et al., 2005; Carranza-Diaz et al., 2014) and faecal bacteria (Karathanasis et al., 2003; Vacca et al., 2005; Headley et al., 2013) while higher removal efficiencies for nitrogen removal was usually found for planted systems (Hijosa-Valsero et al., 2012; Pedescoll et al., 2013a; Webb et al., 2013; Huang et al., 2013; Seeger et al., 2013; Lv et al., 2013; Chen et al., 2014). However, most recent studies also show a higher performance of planted systems in BOD and COD removal (Karathanasis et al., 2003; Leto et al., 2013; Button et al., 2015; Toscano et al., 2015). Furthermore, several studies also found better removals of specific pollutants in planted than unplanted systems

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http://dx.doi.org/10.1016/j.ecoleng.2016.01.038

under both high and low organic load conditions (Seeger et al., 2013; Lv et al., 2013; Carranza-Diaz et al., 2014).

Phragmites australis is the most often used plant in CWs although a large diversity of species can be used and the genus *Typha* and *Scirpus* are commonly used (Vymazal, 2011). Examples of other frequently used species are *Iris pseudacorus*, *Phalaris arundinacea*, *Juncus effusus* and *Arundo donax*. Removal efficiency is usually less affected by the plant species than by the presence or absence of plants. While some studies did not find differences amongst different plant species in organic matter and pathogen removal (Barbera et al., 2009; Tapia et al., 2009; Calheiros et al., 2012) nor in nutrient removal (Calheiros et al., 2012; Huang et al., 2013; Peng et al., 2014), other studies reported higher removal for selected plant species (Coleman et al., 2001; Villaseñor et al., 2007; Barbera et al., 2009; Maltais-Landry et al., 2009; Leto et al., 2013). In some cases, differences existed but were not significant (Toscano et al., 2015) or changed with the years of operation (Hijosa-Valsero et al., 2012; Pedescoll et al., 2013a).

Some studies found a higher efficiency in nutrient removal in CW planted with *Typha* sp. in comparison with other species (Coleman et al., 2001; Karathanasis et al., 2003, Maltais-Landry et al., 2009; Leto et al., 2013). Other studies reported better results for *Scirpus validus* (Fraser et al., 2004), *Iris pseudacorus* (Villaseñor et al., 2007) or *Phragmites australis* (Barbera et al., 2009; Toscano et al., 2015). In one study (Coleman, 2001), *Juncus effusus* reached lower BOD, N and P removal efficiencies than *Typha latifolia* L.

Water loss in CWs occurs primarily through the combined effects of water evaporation and plant transpiration, jointly termed evapotranspiration, while water gain is due to rainfall. Both phenomena can influence contaminant removal efficiency as they affect compound concentration and hydraulic retention time (Beebe et al., 2014). Evapotranspiration is dependent on local meteorological factors as well as on plant species and density (Borin et al., 2011; Beebe et al., 2014; Tuttolomondo et al., 2015). Evapotranspiration can vary extensively, the values reported by Borin et al. (2011) ranging from 0 to 57 mm/d. As evapotranspiration may be as high as the influent hydraulic rate, it could considerably impact wetland performance.

Effective substrate depth in CW usually ranges from 0.5 to 0.6 m. Shallower CW systems (0.2–0.3 m medium depth) force all of the wastewater flowing through the rooting zone of the plants, which increased the treatment performance as has been shown by García et al. (2005). In contrast, Nivala et al. (2013) reported that deeper HSSF systems (0.5 m) had higher areal oxygen consumption rates (OCRs) than shallow systems (0.25 m). On the other hand, shallow beds showed the greatest effect of vegetation on OCR, presumably because the plant rhizosphere was able to occupy a greater portion of the overall bed volume and, on a volumetric basis, the shallow systems perform better than the deeper beds (Nivala et al., 2013).

The combined effect of several design and operation factors and reduced substrate depth on CW treating domestic sewage remains unknown. To the best of our knowledge, there is no published research about the comparison of different plant species in shallow (0.3 m effective depth) CW treating domestic or municipal wastewater. The aim of this research was to study the influence of the presence of plants and plant species on the treatment efficiency of shallow horizontal subsurface flow CWs. This research is part of a wider study looking for the effect of plant species on substrate clogging and greenhouse gas emissions in shallow CWs.

2. Materials and methods

2.1. Pilot plant description

The pilot plant was built in 2009 at the outdoors of the Science Faculty of the University of A Coruña, in A Coruña (Spain) and the study was carried out from October 2009 to March 2012. It was constituted of five horizontal subsurface flow CW units in parallel, including an unplanted control unit while the others were planted with a different plant species each: CW1 (unplanted), CW2 (*Juncus effusus*) CW3 (*Iris pseudacorus*), CW4 (*Typha latifolia* L.) and CW5 (*Phragmites australis*). Initially, whole plants with rhizome and stem were collected from local marginal natural wetlands in June 2009 and were planted at a density of 4 plants per square metre. *Phragmites australis* unit had to be reinforced in April 2010 with a new plantation of about 2 plants per square metre because of partial failure of the previous plantation. Each CW unit has an overall surface of 12 m^2 (3 m wide × 4 m long), depth of 0.35 m (0.3 m of water depth at the outlet) and 1% slope in the flow direction. The cells were filled with crushed granitic gravel of 6–12 mm in size, except for the inlet and outlet zones (0.5 m long) where large stones (60 mm) were used. Mean porosity resulted in 39.3% and effective (void) volume of 1.36 m^3. A peristaltic pump in combination with a flow distributor fed all the units with a similar influent flow.

The influent to the plant comes from a local sewer receiving wastewaters from one of the faculties of the University of A Coruña and surrounding houses and was pre-treated in an up-flow anaerobic sludge bed digester. The pilot plant was fed for approximately 12–14 h per day and five days a week at a hydraulic loading rate (HLR) ranging from 20 to 30 mm/d. Because of the low strength of pre-treated wastewater, during the third year of operation the influent to the CW units was supplemented with commercial wine vinegar. Vinegar addition increased the influent COD and BOD by approximately 182 and 127 mg/L, respectively. In this way, the applied surface loading rate (SLR) to each unit ranged from 2.4 to 3.2 g BOD_5/m^2 d for the two first years of operation, hereafter referred to as low SLR conditions and from 4.4 to 5.0 g BOD_5/m^2 d for the third year, hereafter referred to as SLR design conditions.

2.2. Sampling campaigns and analysis

Seven sampling campaigns were carried out to determine the operational characteristics and performance of each CW unit. During sampling campaigns, punctual influent flow to each unit was measured manually twice a day after the flow distributor while daily accumulated effluent volumes were measured in 600 L tanks receiving the final effluent. Out of the sampling campaigns, influent flow was also monitored at least twice a week.

Sampling procedures involved taking influent and effluent composite samples (integrated over a 24 h period). Influent samples were collected using an automatic sampler type 1350 of American Sigma while effluent samples were collected from daily accumulated volume in final tanks. This procedure was repeated once a week (usually Wednesdays to Thursdays) over a period of four to six weeks in each campaign. Obtained samples were analysed in the laboratory for total and volatile suspended solids (TSS, VSS), chemical oxygen demand (COD), and biological oxygen demand (BOD_5). Temperature, pH, oxidation–reduction potential (ORP) and dissolved oxygen (DO) were determined in situ the same sampling days.

Furthermore, during campaigns IV to VII, influent and effluent samples were analysed for ammonium, total Kjendhal nitrogen (TKN), nitrate and nitrite. Additional monitoring during campaigns IV and V included the determination of pathogen indicators (enumeration of colony forming units (CFU) in punctual samples for total coliforms (TC), faecal coliforms (FC), faecal enterococcus (FE) and C*lostridium perfrigens* (CP)). Analytical methods were carried out as described in Standard Methods (APHA, 2005). An integrated pH and redox 26 Crison electrode was used for pH and ORP determination, a selective electrode (Crison 9663) for ammonium and an electrode ProODO” from YSI for DO. TKN was determined by using a Kjendhal digester Büchi 435 with a Distillation Unit