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A novel design for a compact constructed wetland introducing multi-filtration layers coupled with subsurface superficial space

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ABSTRACT

A novel design for a compact constructed wetland with a multi-layer structure is proposed in this study. A four-layer vertical flow constructed wetland (VFCW) in which four filtration layers were coupled with three subsurface superficial spaces (SSS) was designed, so that the land needed for a VFCW can decrease to one-fourth as large as a conventional single-layer VFCW. The treatment performance of the proposed multi-layer constructed wetland (MLCW) was tested by treating anaerobic digestates containing COD_{Cr} and nutrients in high concentrations. The removal efficiencies for COD_{Cr}, total phosphorus (TP) and NH_4-N were >99%, >96% and >99%, respectively, and a high nominal oxygen transfer rate (OTR) of 102 gO_2/m^2 d was attained. This indicated successful aerobic treatment despite a much smaller land area being used compared with that required for a single-layer VFCW. To enhance denitrification, the treatment performance of MLCW was also tested under partially saturated conditions, when the third and fourth filtration layers were saturated with water. The removal efficiency for total nitrogen (TN) improved to 76.5%, while that for COD_{Cr}, TP and NH_4-N was comparable to that obtained in unsaturated conditions. This result indicated that MLCW with partially saturated layers may provide an alternative hybrid system enhancing both aerobic and anaerobic treatment, although further research to improve anaerobic reactions is required. Nevertheless, the potential of MLCW as a novel approach to reduce the land area needed for constructed wetlands (CWs) was clearly demonstrated.

1. Introduction

Constructed wetlands (CWs) are used worldwide for removing pollutants from wastewater as they are mechanically simple and have low operational and maintenance requirements in comparison to conventional wastewater treatment technologies (Wu et al., 2014; Ayaz et al., 2015; Wu et al., 2015). However, the land area needed is a drawback of this technology (Campbell and Ogden, 1999; Ayaz et al., 2015; Silveira et al., 2015). Because oxygen diffusion from the atmosphere into the filtration beds depends on the superficial area of the CWs, an area of land sufficient to promote aerobic degradation of organic compounds or nitrification in the CWs is required. To enhance aerobic treatment, vertical flow constructed wetlands (VFCWs) have been adopted, in which the water level is controlled at the bottom of the filter beds so that atmospheric diffusion of oxygen from the open air into the filter beds is not inhibited by the water column (Brix and Arias, 2005; Cooper, 2005; Molle et al., 2005). Intermittent loading of wastewater onto the wetland allows flooding of the surface, followed by gradual seepage down through the filter beds, promoting their ventilation with air. According to Cooper (2005), the achievable oxygen transfer rate (OTR) by such natural ventilation was at least 28 gO_2/m^2 d. Variations in OTR also depend on operational conditions. It was reported by Kato et al. (2013) that OTR increased in proportion to the influent load and the highest OTR of 157 gO_2/m^2 d was attained in a VFCW with a recirculation system. Thus compact CWs may be created by optimization of the operational conditions of CWs.

To create a compact CW and so reduce the land area needed, a different approach—structural modification—was proposed in this study. The novel design for a compact CW introduced filtration beds

Abbreviations: CW, constructed wetland; MLCW, multi-layer constructed wetland; OTR, oxygen transfer rate; SSS, subsurface superficial space; VFCW, vertical flow constructed wetland.

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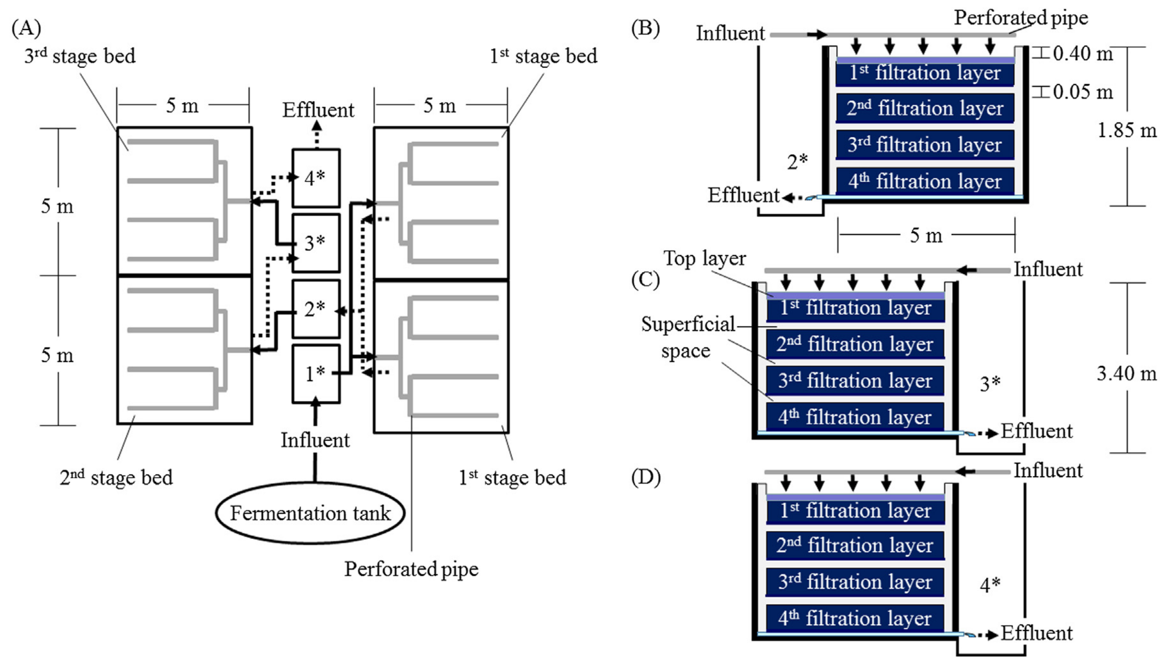

Fig. 1. The birds-eye view of the arrangement of the MLCW for three-stage treatment (A) and the cross sectioned diagrams of the subsurface structure of the first (B), second (C), and third (D) MLCW implemented with four filtration layers and three superficial spaces. Solid and dotted arrows show the flow of influent and effluent, respectively. 1*, influent collection basin; 2*, 1st water collection basin; 3*, 2nd water collection basin; 4*, 3rd water collection basin.

coupled with subsurface superficial space (SSS). If SSS is created in CW filtration beds, oxygen transfer into the beds will take place from not only the upper surface, but also the bottom surface. Such oxygen transfer from both sides of the filtration beds may allow significant improvement in the OTR, enabling downsizing of the land area required for VFCW. Furthermore, the SSS allows us to create multi-layer aerobic filtration beds in a single-stage CW. The treatment capacity of such a multi-layer CW (MLCW) may equal that of a multi-stage VFCW. It was reported (Silveira et al., 2015) that partially saturated VFCWs could promote the total simultaneous treatment of nitrogen in a single-stage CW. Thus, if the MLCW is partially saturated, a hybrid system consisting of both aerobic and anaerobic treatments may be incorporated into a single-stage CW.

In this study, the treatment performance of a pilot-scale MLCW was tested by treating anaerobic digestate under two different water saturation conditions: unsaturated and partially saturated. Anaerobic digestate produced as a residue of biogas production contains high concentrations of organic matter and nutrients. The high ammonia nitrogen of anaerobic digestate is generally difficult to access in conventional biological treatment processes, and physico-chemical pretreatments such as ammonia stripping and ion exchange are required to lower its concentration. However, these treatments are expensive. For full ammonia stripping, a large amount of calcium hydroxide (27.5 g/L digestate) has been required (Lei et al., 2007), which cost about more than US\$ 1290/m^3 digestate. High removal efficiency has been achieved by extensive use of land for CWs (de la Varga et al., 2013), and downsizing is required.

The objective of this study was to demonstrate the potential of MLCW as a novel approach to reduce the land area needed for CWs. To demonstrate the efficacy of aerobic treatment in dealing with nitrification in an MLCW with multi-layer filtration beds plus SSS, its performance was tested under unsaturated conditions. The conditions were then shifted to partial saturation so the potential of hybrid treatment achieving total nitrogen (TN) removal was examined. Based on these results, the potential of the MLCW as a novel approach to reduce the necessary land area for CWs was discussed.

2. Materials and methods

2.1. Design of multi-layer constructed wetland

A pilot-scale MLCW implemented with four filtration layers and three SSS was designed. This was based on the land area available, and assumed an OTR sufficient to treat anaerobic digestate from a biogas production reactor. The necessary land area was calculated with a modified Brix equation (Brix and Arias, 2005):

$$\text{OTR} \times \text{CW area} = \text{Hydraulicload} \times (\text{BOD removed} + 4.3 \times \text{TKN removed}) \quad (1)$$

where the hydraulic load is in m^3/day, CW area is m^2 and the biological oxygen demand (BOD) and total Kjeldahl nitrogen (TKN) are g/m^3. The necessary land area to satisfy the oxygen demand for complete oxidation of organic matter and TKN in the anaerobic digestate was calculated to be approximately 390 m^2. This was based on the assumption that 30 gO_2/m^2 d of OTR and 1 m^3 of hydraulic load of anaerobic digestate with 6000 g/m^3 of BOD and 1400 g/m^3 of TKN would be treated by the CW. However, the land area available for a CW was only 100 m^2; in other words, approximately one-fourth as large as that needed for a conventional single-layer VFCW. This was one reason why an MLCW with four layers of filtration beds was designed. The arrangement of the MLCW is shown in Fig. 1A.

The treatment system in this study had three stages. The total surface area of the MLCW was 100 m^2 and it was divided into four beds. Two were used for the first stage (50 m^2) and the other two for the second (25 m^2) and third stages (25 m^2). Fig. 1B–D shows a schematic diagram of the subsurface structure of the MLCW. The beds were 1.70 m deep and consisted of four filtration layers coupled with three superficial spaces. The first filtration layer was 0.40 m deep while the others were 0.35 m deep. The superficial spaces between each filtration layer were constructed by spreading