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Life cycle assessment of constructed wetland systems for wastewater treatment coupled with microbial fuel cells

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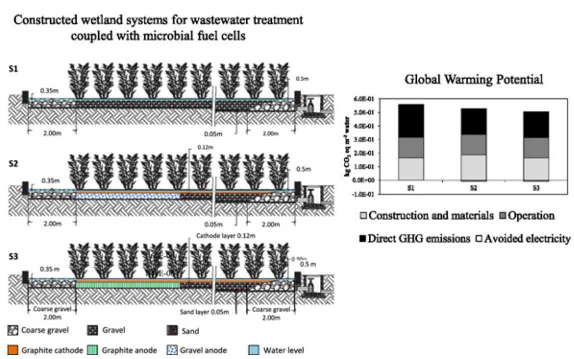
HIGHLIGHTS

- MFCs implemented in CWs improve treatment efficiency and reduce surface requirement.
- LCA of CWs coupled with MFCs and conventional CWs was performed.
- CWs coupled with MFCs and conventional CWs showed similar environmental impacts.
- MFCs implemented in CWs can reduce system footprint while keeping the environmental impacts low.
- MFCs implemented in CWs are around 1.5 times more expensive than conventional CWs.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study was to assess the environmental impact of microbial fuel cells (MFCs) implemented in constructed wetlands (CWs). To this aim a life cycle assessment (LCA) was carried out comparing three scenarios: 1) a conventional CW system (without MFC implementation); 2) a CW system coupled with a gravel-based anode MFC, and 3) a CW system coupled with a graphite-based anode MFC. All systems served a population equivalent of 1500 p.e. They were designed to meet the same effluent quality. Since MFCs implemented in CWs improve treatment efficiency, the CWs coupled with MFCs had lower specific area requirement compared to the conventional CW system. The functional unit was 1 m^3 of wastewater. The LCA was performed with the software *SimaPro® 8*, using the CML-IA baseline method. The three scenarios considered showed similar environmental performance in all the categories considered, with the exception of Abiotic Depletion Potential. In this impact category, the potential environmental impact of the CW system coupled with a gravel-based anode MFC was around 2 times higher than that generated by the conventional CW system and the CW system coupled with a graphite-based anode MFC. It was attributed to the large amount of less environmentally friendly materials (e.g. metals, graphite) for MFCs implementation, especially in the case of gravel-based anode MFCs. Therefore, the CW system coupled with graphite-based anode MFC appeared as the most environmentally friendly solution which can replace conventional CWs reducing system footprint by up to 20%. An economic assessment showed that this system was around 1.5 times more expensive than the conventional CW system.

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1. Introduction

Horizontal subsurface flow constructed wetlands (HSSF CWs) are natural wastewater treatment systems in which pollutants are removed by means of physical, chemical and biological processes (García et al., 2010). They constitute an alternative to conventional systems for wastewater treatment (e.g. activated sludge systems) in small communities due to their low energy requirement and easy operation and maintenance (Puigagut et al., 2007). Nevertheless, HSSF CWs are characterized by higher specific area requirement when compared to conventional technologies (2–5 vs. <1 m^2 $p.e.^{-1}$, respectively). In order to overcome this drawback, several intensifying strategies (e.g. forced aeration) has been lately investigated (Austin and Nivala, 2009; Wu et al., 2014). However, these strategies often result in a significant increase in energy consumption when compared to conventional HSSF CW designs.

Microbial Fuel Cells (MFCs) are bioelectrochemical devices that generate electricity from organic matter by means of exoelectrogenic bacteria (Logan, 2008). These bacteria oxidize organic compounds and transfer the resulting electrons to an electrode (anode). From the anode, electrons flow through an external circuit (containing a resistor) to the cathode, where they are used to reduce an electron acceptor (e.g. oxygen) (Rabaey and Verstraete, 2005). Therefore, MFCs performance depends on the redox gradient between electrodes (anode and cathode).

The presence of organic matter in wastewater and the naturally generated redox gradient between the upper layer (in aerobic conditions) and the deeper layers (in anaerobic conditions) of HSSF CW treatment bed, are favourable conditions for the implementation of MFCs in CW systems (Corbella et al., 2014; García et al., 2003). During the last decade, several studies have demonstrated the synergy between MFCs and HSSF CWs (Corbella et al., 2015; Corbella et al., 2016). Indeed, the implementation of MFCs in HSSF CWs may lead to important benefits. First of all, it provides an energy surplus that can partially cover the energy input necessary for wastewater treatment (Corbella et al., 2015). Moreover, MFCs can stimulate the degradation of organic matter present in wastewater by fostering more efficient degradation pathways carried out by exoelectrogenic bacteria (Katuri et al., 2011; Srivastava et al., 2015). As a consequence, the implementation of MFCs in HSSF CWs can improve CWs treatment efficiency and reduce their surface requirement. However, materials used for conventional MFCs electrodes (e.g. carbon fiber, stainless steel) are expensive materials with poor environmental performance (Foley et al., 2010; Gude, 2016; Liu and Cheng, 2014; Zhou et al., 2011). Therefore, although energy inputs and surface area requirement could be reduced, both costs and environmental impacts could significantly increase when implementing MFCs in CW treatment systems.

Even if several studies which analyse the environmental impacts of CW systems have been carried out (Dixon et al., 2003; Fuchs et al., 2011; Machado et al., 2007; Yildirim and Topkaya, 2012), there is still no study assessing the environmental impacts of CW systems coupled with MFCs.

The objective of this study was to evaluate the environmental impacts caused by HSSF CWs coupled with MFCs made of different materials. To this aim a Life Cycle Assessment (LCA) was performed comparing three alternatives: i) a conventional CW system (without MFCs implementation); ii) an HSSF CW system coupled with a gravel-based anode MFC; iii) an HSSF CW system coupled with a graphite-based anode MFC.

An economic evaluation of the considered scenarios was also conducted.

2. Materials and methods

2.1. Constructed wetland systems design

The conventional CW system was a hypothetical wastewater treatment plant designed to serve a population equivalent of 1500 p.e. and treat 292.5 m^3 of wastewater per day. It comprised a primary treatment (i.e. septic tank) followed by HSSF CWs. The CW unit consisted of 3 basins filled up with granitic gravel (D60 = 7.3; Cu = 0.8; porosity = 40%) and planted with *Phragmites australis* (Pedescoll et al., 2013).

The CW unit was designed according to García and Corzo (2008). First of all, the total surface area was determined using the following expression:

$$S = \frac{Q}{k_A} \ln\left[\frac{C_0}{C_1}\right] \tag{1}$$

where
S = total CW surface, m^2
Q = inlet flow rate, $m^3\ d^{-1}$
k_A = first order rate constant for BOD removal, $m\ d^{-1}$
C_0 = BOD inlet concentration, $mg\ L^{-1}$
C_1 = BOD outlet concentration, $mg\ L^{-1}$

In this case, the first order rate constant for BOD removal (k_A) was considered to be 0.08 $m\ d^{-1}$ (García and Corzo, 2008). Then, the hydraulic sizing was conducted by applying the Darcy's law and considering a porosity of 35%, a hydraulic conductivity of 5000 $m^3\ m^{-2}\ d^{-1}$, a safety factor of 7, a slope of 0.01 $m\ m^{-1}$, a wetland depth of 0.35 m and a water depth of 0.3 m (García et al., 2005; García and Corzo, 2008).

The design of the CW systems coupled with gravel and graphite-based anode MFCs was carried out taking into account that the implementation of MFCs in CWs stimulates degradation processes leading to higher k_A values compared to conventional CWs (without MFCs) (Srivastava et al., 2015). In these cases, the k_A was estimated considering the results obtained in previous experiments conducted at the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) (Barcelona, Spain). These experiments showed a decrease in outlet BOD concentrations as a consequence of the implementation of MFCs in lab-scale HSSF CWs, which indicates an increase of the BOD removal rate constant in CW systems coupled with MFCs (Corbella and Puigagut, under review; Corbella and Puigagut, 2016). In accordance with the results of this study, the k_A was increased to 0.092 $m\ d^{-1}$ and 0.098 $m\ d^{-1}$ for the CW system coupled with gravel-based anode MFC and the CW system coupled with graphite-based anode MFC, respectively. It is important to note that since all CW systems here considered were designed to provide the same effluent quality (25 $mg_{BOD}\ L^{-1}$), higher k_A values resulted in lower specific area requirements (Eq. (1)).

MFCs cathode was designed to be a 12 cm depth layer of crushed graphite placed at the upper part of the CW (in contact with the atmosphere) covering most of the surface of the gravel bed. This design was taken from the recommendations given elsewhere (Corbella et al., 2016) as to make sure that the cathode remains always in contact with the water table and the atmosphere (Fig. 1). Furthermore, the anodic volume was determined according to the optimal cathode to anode ratio (4:1) as recommended by Corbella et al. (2015). MFCs anode was placed at a distance of 2 m from the inlet distribution zone (after the initial coarse gravel zone). The anode was considered to be made of gravel or crushed graphite (Fig. 1). Even though gravel is not a conductive material, it has been reported that it provides a suitable surface for the establishment of exoelectrogenic communities if an electron collector (e.g. stainless steel mesh) is provided (Corbella et al., 2015). Therefore, in gravel-based anode a stainless steel mesh (0.5 cm-mesh) was placed at every 5 cm depth along the whole anode surface. CW systems characteristics and design parameters are summarised in Table 1.

2.2. Life cycle assessment

LCA is a standardized methodology for the evaluation of the potential environmental impacts generated by a product, process or service using a cradle to grave approach (ISO, 2000; ISO, 2006). It identifies and quantifies the environmental burdens associated with energy and