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

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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 1,500 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.

Keywords: Constructed wetland; Environmental impact assessment; Decentralised wastewater treatment system; Life Cycle Assessment; Microbial fuel cells; Wastewater treatment

1. Introduction

Horizontal subsurface 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 et al., 2012), there is still no study assessing 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 1,500 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:

$$S = \frac{Q}{k_A} \ln \left[\frac{C_0}{C_1} \right] \qquad \text{(Eq. 1)}$$

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 5,000 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, submitted, 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 (Figure 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 (Figure 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.

Please Insert Table 1

Please Insert Figure 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 materials used (inputs) and waste released into the environment (outputs) during the whole life cycle. LCA is mainly used to compare different competing products or technologies, as well as to identify improvement alternatives for a single product or technology. The methodological framework for LCA consists of the following phases: goal and scope definition; inventory analysis; impacts assessment and interpretation of the results (ISO, 2006). The following sections describe the specific contents of each phase.

2.2.1 Goal and scope definition

The goal of this study was to assess and compare the potential environmental impacts generated by HSSF CWs for wastewater treatment coupled with MFCs made of different materials. To this aim, the following scenarios were considered:

1) Conventional CW system (without MFC) (S1);
2) CW system coupled with a gravel-based anode MFC (S2);
3) CW system coupled with a graphite-based anode MFC (S3).

The functional unit was 1 m^3 of treated water.

The system boundaries included unit processes related to systems construction and operation over a period of 20 years. Input flows associated with construction materials and energy resources (electricity) were comprehensively studied for all alternatives. Outputs consisted of direct greenhouse gas (GHG) emissions. The end-of-life of infrastructures and equipment were excluded from the scope of LCA, since it was considered to not significantly influence the overall impact (Lopsik, 2013; Machado et al., 2007). Sludge disposal was not accounted for, since its contribution only represents a minor fraction of the overall impact (Garfí et al., submitted). Transportation of construction materials was not considered. Their contribution to the overall impact can be neglected, since locally produced materials are supposed to be used (Fuchs et al., 2011). The effluent discharge was not included within the system boundaries, since the CW systems were designed in order to produce a same quality final effluent.

The system expansion method has been used to quantify the impacts generated by by-products, as suggested by ISO standard (ISO, 2006). It consists of considering the environmental benefits of recovered resources (by-products) by expanding the system boundaries to include the avoided impacts of conventional production. In this study, the avoided burdens of using electricity produced by MFCs instead of electricity supplied through the grid were considered.

2.2.2 Inventory analysis

The results of the inventory analysis for the three investigated CW systems are summarized in Table 2. Inventory data regarding construction processes, construction materials and electricity consumption were gathered from the construction projects performed in the frame of this study. CH_4 emissions from the conventional CW system were estimated considering the emissions rate found in previous studies carried out in a pilot plant of HSSF CWs implemented at the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) (Barcelona, Spain) (Corbella and Puigagut, 2015a). In order to estimate CH_4 emissions from the CW systems coupled with MFCs, the MFC efficiency in reducing CH_4 fluxes found by Rizzo et al. (2013) was considered. Regarding the N_2O emissions, the emission rate proposed by Mander et al. (2008) was taken into account for all scenarios. CO_2 emissions were not included in the inventory, since CO_2 from biogenic sources does not contribute to global warming potential (Doorn et al., 2006). Electricity produced by MFCs were determined considering the results obtained from lab-scale experiments carried out at the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) (Barcelona, Spain) (Corbella and Puigagut, submitted, Corbella and Puigagut, 2016). All materials and energy inputs, as well as direct GHG emissions, were determined based on the functional unit. Background data were obtained from the *Ecoinvent 3.1* database (Moreno-Ruiz et al., 2014; Weidema et al., 2013). The Spanish electricity mix (i.e: natural gas 39%; nuclear 19%; coal 15.50%; wind 10.90%; hydro 8.80%; liquid fuels 5.80% and solid biomass 1%) was used for the electricity requirement.

Please Insert Table 2

2.2.3 Impact assessment

The LCA was performed using the software *SimaPro*® *8* (Pre-sustainability, 2014). Potential environmental impacts were assessed by the CML-IA baseline method following the ISO standard procedure (ISO, 2000). The analysis focused on the following impact categories: Abiotic Depletion, Abiotic Depletion (fossil fuels), Global Warming Potential, Ozone Layer Depletion, Acidification, Eutrophication and

Photochemical Oxidation. In this study only classification and characterisation phases were performed.

2.2.4 Sensitivity Analysis

A sensitivity analysis evaluates the influence of the most important assumptions have on the results. It consists of defining some scenarios, alternative to that assumed as a base case, and comparing the potential environmental impacts with those of the base case scenarios. To this end, selected parameters are changed into reasonable ranges of variation to check if the outcomes of the LCA can be heavily dependent on some of the assumptions. In this study, two parameters were evaluated (Table 3): i) the k_A in scenarios S2 and S3 (CW systems with gravel and graphite-based anode MFCs, respectively); and, ii) the electricity produced by MFCs in scenarios S2 and S3 (CW systems with gravel and graphite-based anode MFCs, respectively).

Regarding the k_A, two alternatives were considered: 0.138 and 0.162 m d^{-1}, which correspond to an increase of 50 and 75% with respect to the k_A taken into account in scenario 2 (0.092 m d^{-1}). These values have been chosen considering that MFCs in CWs can produce an improvement in treatment efficiencies higher than those used in the base case scenarios (Aguirre-Sierra et al., 2016). In order to carry out the sensitivity analysis, the CW systems in scenarios S2 and S3 were redesigned taking into account the above-mentioned k_A values. Since these k_A values were higher than those of the base case scenarios, the CW systems considered for the sensitivity analysis had higher treatment efficiency and lower specific area requirement compared to that of the base case scenarios (Table 3).

Concerning the electricity produced by MFCs, two alternatives were analysed: 40 Wh m^{-3} and 70 Wh m^{-3}. These values were chosen as they represent a middle and high energy production scenario for conventional MFC systems treating wastewater, respectively (Ge, et al., 2014; Logan and Rabaey, 2013).

Please Insert Table 3

2.3 Economic assessment

The economic analysis was conducted comparing the capital cost of the three CW systems (scenarios S1, S2 and S3). In addition, the scenarios with lower specific area requirement (scenarios S2A, S2B, S3A and S3B, Table 3) considered in the sensitivity analysis were also taken into account. In all scenarios, prices were provided by local companies. The capital cost included the cost for earthmoving, construction materials purchase and electrical works. For all scenarios, a lifespan of 20 years was considered. CWs implemented with MFCs would probably require more material replacement than conventional CWs configurations. However, MFC implemented in CWs would reduce biomass growth within the filter media (Park and Zeikus, 200), reducing clogging and its derived operation and maintenance costs. Overall, operation and maintenance costs were assumed to be the same in all scenarios and, thus, they were not included in the analysis.

3. Results and discussion

3.1 Life Cycle Assessment

The potential environmental impacts associated with each scenario are shown in Figure 2.

All the alternatives showed a similar environmental performance in all the categories analysed, with the exception of Abiotic Depletion Potential. In this impact category, the potential environmental impact of scenario S2 (CW system coupled with a gravel-based anode MFC) was around 2 times higher than that generated by scenarios S1 and S3 (conventional CW system and CW system coupled with a graphite-based anode MFC, respectively) (Figure 2). It was due to the fact that, despite the CW systems coupled with MFCs showed lower specific area requirement compared to the conventional CW system, they require a large amount of less environmentally friendly materials (i.e. metals and graphite) for MFCs implementation (Table 2). In particular, the high impact caused by the CW system coupled with a gravel-based anode MFC (scenario S2) in the Abiotic Depletion category was mainly attributed to the large amount of stainless steel required for the electron collector at the anode (stainless steel mesh) (Table 2). It was in accordance with previous studies which observed that the potential environmental impact of a CW system would increase by around 30% of the overall impact if gravel and sand were replaced with less environmentally friendly materials (i.e. lightweight expanded clay aggregate) (Lopsik, 2013).

Since CW systems are extensive, low-tech and low energy technologies, their life cycle is mainly influenced by construction. For all scenarios, the contribution of the construction and operation stages in Abiotic Depletion impact category accounted for 88-95% and 5-12% of the total impact, respectively. It was in accordance with previous studies which assessed the environmental impacts of conventional CW systems (Dixon et al., 2003; Fuchs et al., 2011; Machado et al., 2007). With regards to Abiotic Depletion (fossil fuels), Acidification and Eutrophication Potentials, construction and operation accounted for around 50% of the overall impact in all scenarios. In these categories, the appreciable contribution of operation to the overall impact was mainly due to the use of fossil fuels for electricity production and to gases emissions (i.e. NO_x and SO_2) generated by power plants (Turconi et al., 2013). As far as Global Warming and Photochemical Oxidation Potentials are concerned, direct GHG emissions, construction and operation phases contributed equally to the overall impact in scenarios S2 and S3 (CW system coupled with gravel and graphite-based anode MFCs, respectively). On the contrary, in scenario 1 (conventional CW system) the contribution of direct GHG emissions was around 45% of the total environmental impact for the above-mentioned impact categories. It was attributed to MFCs capability of reducing methane released to the atmosphere during wastewater treatment under anaerobic conditions. In fact, in these systems bacteria involved in bioelectrochemical processes use organic matter (e.g. acetate) as a substrate, reducing the availability of the carbon source for methanogenic bacteria (Rizzo, et al., 2013). For all scenarios, the contribution of operation phase to the overall impact only predominated in Ozone Layer Depletion impact category (around 60% of the total impact). Moreover, electricity produced by MFCs had a negligible impact in all considered impact categories. In all scenarios, using electricity produced by MFCs instead of electricity supplied by the grid would reduce potential environmental impact by around 3% in all impact categories.

Finally, CW system coupled with graphite-based anode MFC appeared as the best alternative to reduce CW surface requirements (by around 20%, Table 3) from an environmental perspective.

Please insert Figure 2

3.2 Sensitivity analysis

The results of the sensitivity analysis are shown in Figure 3. As mentioned above, it took into account two parameters: i) the k_A in scenarios S2 and S3 (CW systems with gravel and graphite-based anode MFCs, respectively); and ii) the electricity produced by the MFCs in scenarios S2 and S3 (CW systems with gravel and graphite-based anode MFCs, respectively).

Regarding the k_A, the results showed how increasing this parameter (to 0.138 and 0.162 m d^{-1}) would slightly reduce the environmental impact (by up to 10%, as compared to the base cases – 0.092 and 0.098 m d^{-1}) in all impact categories with the exception of Abiotic Depletion Potential. For this impact category, the reduction in scenario S2 accounted for around 25% as compared to the base cases (0.092 m d^{-1}). Nevertheless, scenario S2 remained the most abiotic depleting alternative.

Concerning the electricity produced by MFCs, the sensitivity analysis showed that increasing the electricity produced (to 40 Wh m^{-3} and 70 Wh m^{-3}) would reduce all environmental indicators by 1-10% as compared to the base cases (14.4 Wh m^{-3}).

Consequently, it can be concluded that the results of the LCA are robust and not strongly dependent on the assumptions considered in this study.

Please insert Figure 3

3.3 Economic assessment

The results of the economic assessment are summarised in Table 4. The capital cost of conventional CW system (scenario S1) was around 430 € $p.e.^{-1}$, which is in agreement with previous studies (Masi and Bresciani, 2013; Puigagut et al., 2007). The CW system coupled with a gravel-based anode MFC (scenario S2) appeared as the most expensive alternative, followed by the CW system coupled with a graphite-based anode MFC (scenario S3). In particular, CW systems coupled with MFCs (scenario S2 and S3) showed to be from 1.4 to 1.6 times more expensive than the conventional CW system. It was mainly due to the high cost of materials (i.e. graphite and steel) used for microbial fuel cells implementation. In the case of scenarios with lower specific area requirement considered in the sensitivity analysis (scenarios S2A, S2B, S3A and S3B, Table 3), the capital costs were similar to that of the conventional CW system (scenario S1). Thus, CW systems coupled with high performance MFCs would be competitive with conventional CWs in terms of costs.

Please insert Table 4

4. Conclusions

- The CW systems coupled with MFCs are an appropriate solution for wastewater treatment in small communities which may help to reduce surface requirements, while keeping the environmental impacts low.
- The CW system coupled with a graphite-based anode MFC appeared as the most environmentally friendly solution which could replace conventional CWs reducing system footprint by up to 20%.
- The CW system coupled with a graphite-based anode MFC showed to be around 1.5 times more expensive than the conventional CW system. The cost of MFC-based CW would be competitive with conventional CW only under higher treatment performances of MFC than those currently attained.
- For the purpose of reducing costs, cheaper materials should be investigated for MFCs implementation in CW systems.
- Regarding the future research needs, an environmental and economic analysis of a full-scale CWs system coupled with MFCs should be carried out using data obtained during a long-term monitoring (e.g. MFCs lifespan, electricity generated by MFCs, wastewater treatment efficiency, GHG emissions, costs).

Moreover, a comparison with other intensified CW systems (e.g. aerated CWs and MFCs implemented in saturated vertical flow CWs) should be also addressed.

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Table 1. CW systems characteristics and design parameters

			Scenarios [(a)]		
		Unit	**S1**	**S2**	**S3**
System characteristics					
Inlet BOD concentration [(b)]		$mg_{BOD}\ L^{-1}$	168	168	168
Outlet BOD concentration [(c)]		$mg_{BOD}\ L^{-1}$	25	25	25
Flow rate		$m^3\ d^{-1}$	292.5	292.5	292.5
Population equivalent		*p.e.*	1,500	1,500	1,500
BOD removal efficiency		*%*	85	85	85
Design parameters					
Hydraulic conductivity		$m^3\ m^{-2}\ d^{-1}$	5,000	5,000	5,000
First order rate constant for BOD removal (k_A)		$m\ d^{-1}$	0.08	0.092	0.098
Organic Loading Rate (OLR)		$g_{BOD}\ m^{-2}\ d^{-1}$	6.00	6.90	7.40
Hydraulic Loading Rate (HLR)		$m\ d^{-1}$	0.036	0.041	0.044
Constructed wetlands					
Number of constructed wetland cells		-	3	3	3
Constructed wetland cell dimensions		*m (D×L×W)*	0.3 × 60 × 45.5	0.3 × 52.5 × 45.5	0.3 × 49 × 45.5
Total surface area		m^2	8,190	7,166	6,688.5
Specific area requirement		$m^2\ p.e.^{-1}$	5.46	4.78	4.46
Microbial Fuel Cells					
Anode	Material	-	-	gravel	graphite
	Volume	m^3	-	64.23	59.59
Cathode	Material	-	-	graphite	graphite
	Volume	m^3	-	264.81	245.7

(a) S1: conventional CW system (without MFC); S2: CW system coupled with a gravel-based anode MFC; S3: CW system coupled with a graphite-based anode MFC

(b) Influent concentration at the treatment plant was 240 mg BOD L^{-1}*. Primary treatment was supposed to remove 30% of the BOD concentration.*

(c) Discharge legislation limit (MAGRAMA, 2007).

Table 2. Wastewater treatment inventory for scenarios S1, S2 and S3. Values are referred to the functional unit (1 m^3 of water).

		Scenarios (a)		
	Units	**S1**	**S2**	**S3**
Inputs				
Construction materials				
Inlet pumping station				
Concrete	$m^3\,m^{-3}$	5.77E-06	5.77E-06	5.77E-06
Metals	$kg\,m^{-3}$	8.51E-04	8.51E-04	8.51E-04
Coating	$kg\,m^{-3}$	1.19E-04	1.19E-04	1.19E-04
Plastics	$kg\,m^{-3}$	4.41E-06	4.41E-06	4.41E-06
Septic tank				
Concrete	m^3m^{-3}	3.37E-05	3.37E-05	3.37E-05
Metals	$kg\,m^{-3}$	3.32E-03	3.32E-03	3.32E-03
Coating	$kg\,m^{-3}$	6.23E-04	6.23E-04	6.23E-04
Plastics	$kg\,m^{-3}$	2.02E-05	2.02E-05	2.02E-05
Pumping stations				
Concrete	m^3m^{-3}	6.47E-06	6.47E-06	6.47E-06
Metals	$kg\,m^{-3}$	9.70E-04	9.70E-04	9.70E-04
Coating	$kg\,m^{-3}$	1.21E-04	1.21E-04	1.21E-04
Plastics	$kg\,m^{-3}$	1.32E-05	1.32E-05	1.32E-05
Constructed wetlands and Microbial fuel cells				
Concrete	m^3m^{-3}	1.75E-05	1.63E-05	1.57E-05
Metals	$kg\,m^{-3}$	8.42E-04	5.32E-03	7.71E-04
Coating	$kg\,m^{-3}$	1.19E-05	1.19E-05	1.19E-05
Plastics	$kg\,m^{-3}$	7.92E-03	7.01E-03	6.58E-03
Gravel and sand	$kg\,m^{-3}$	2.76E+00	1.83E+00	1.59E+00
Bricks	$kg\,m^{-3}$	3.86E-02	3.59E-02	3.46E-02
Graphite	$kg\,m^{-3}$	-	2.99E-01	3.44E-01
Storage tank				
Concrete	m^3m^{-3}	5.69E-05	5.69E-05	5.69E-05
Metals	$kg\,m^{-3}$	5.31E-03	5.31E-03	5.31E-03
Coating	$kg\,m^{-3}$	5.82E-04	5.82E-04	5.82E-04
Plastics	$kg\,m^{-3}$	2.39E-06	2.39E-06	2.39E-06
Pipelines				
Plastics	$kg\,m^{-3}$	1.29E-04	1.29E-04	1.29E-04
Operation				
Electricity	$kWh\,m^{-3}$	3.10E-01	3.10E-01	3.10E-01
Outputs				
Emissions to air (direct GHG emissions)				
CH_4	$g\,m^{-3}$	10.89	8.49	8.49
N_2O	$g\,m^{-3}$	0.01	0.01	0.01
Avoided products				
Electricity produced by MFCs	$kWh\,m^{-3}$		1.44E-02	1.44E-02

(a) *S1: conventional CW system (without MFC); S2: CW system coupled with a gravel-based anode MFC; S3: CW system coupled with a graphite-based anode MFC*

Table 3. Scenarios and parameters considered in the sensitivity analysis.

Scenarios (a)	**Microbial fuel cells**		**k_A**	**Electricity produced by MFCs**	**Specific area requirement**
	Anode	**Cathode**	$m\ d^{-1}$	$Wh\ m^{-3}$	$m^2\ p.e.^{-1}$
S1	**-**	**-**	0.080	-	5.42
S2 (base case)	Gravel	Graphite	0.092	14.4	4.74
S2A	Gravel	Graphite	0.138	14.4	3.14
S2B	Gravel	Graphite	0.162	14.4	2.68
S2C	Gravel	Graphite	0.092	40	4.74
S2D	Gravel	Graphite	0.092	70	4.74
S3 (base case)	Graphite	Graphite	0.098	14.4	4.42
S3A	Graphite	Graphite	0.138	14.4	3.14
S3B	Graphite	Graphite	0.162	14.4	2.68
S3C	Graphite	Graphite	0.098	40	4.42
S3D	Graphite	Graphite	0.098	70	4.42

(a) S1: conventional CW system (without MFC); S2: CW system coupled with a gravel-based anode MFC; S3: CW system coupled with a graphite-based anode MFC

Table 4. Capital costs of the considered scenarios expressed in terms of euros per population equivalent.

Scenarios (a)	**Microbial fuel cells**		**Capital cost**
	Anode	**Cathode**	€ $p.e.^{-1}$
S1	**-**	-	432
S2 (base case)	Gravel	Graphite	726
S2A	Gravel	Graphite	518
S2B	Gravel	Graphite	488
S3 (base case)	Graphite	Graphite	639
S3A	Graphite	Graphite	470
S3B	Graphite	Graphite	445

(a) Scenarios are defined in Table 3

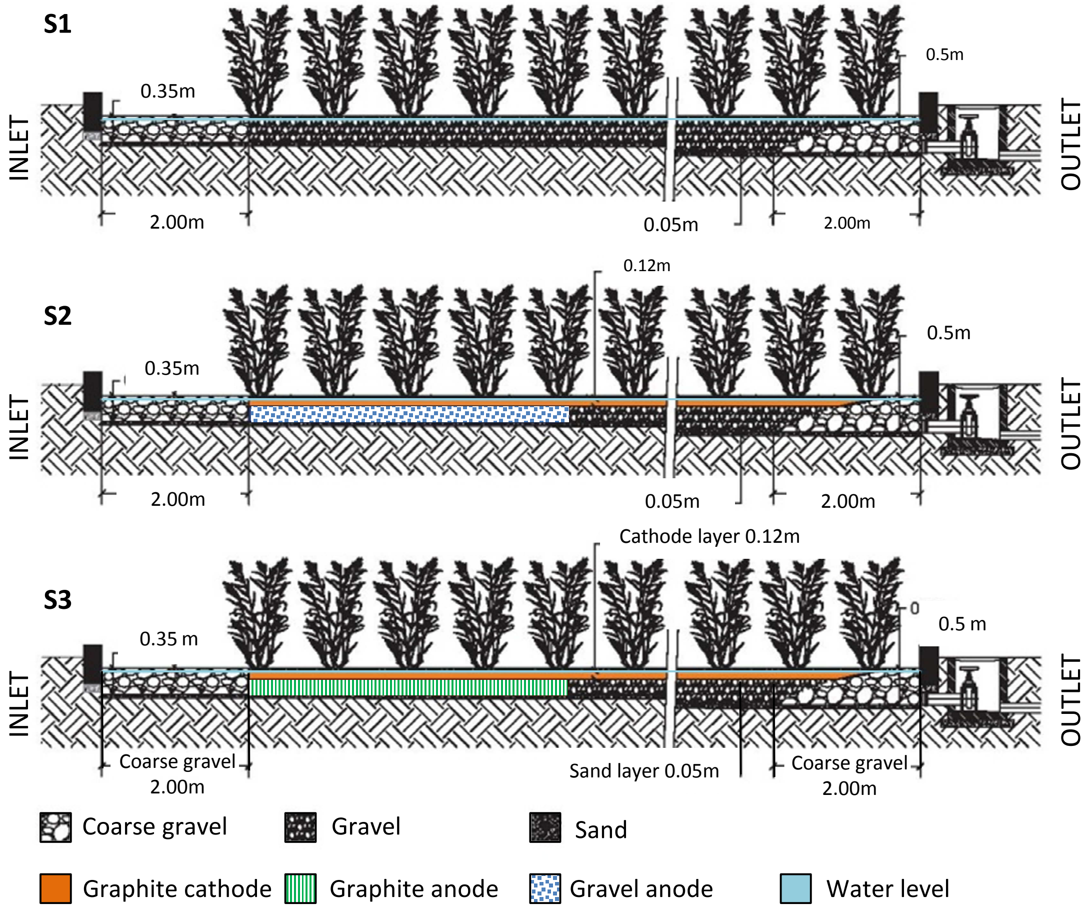
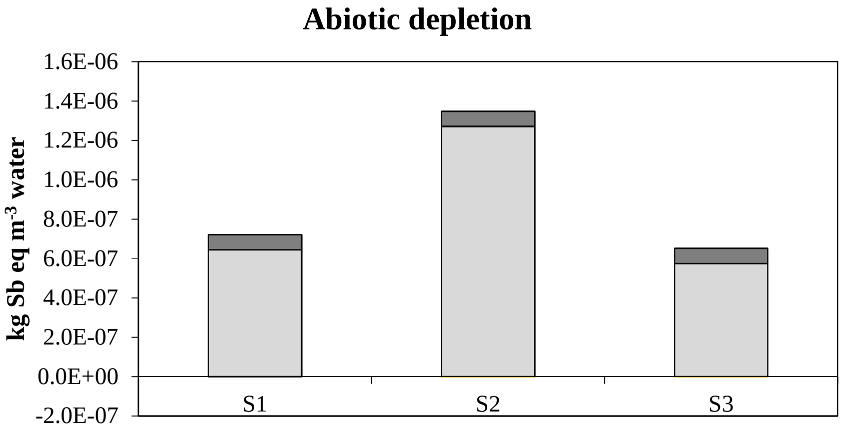
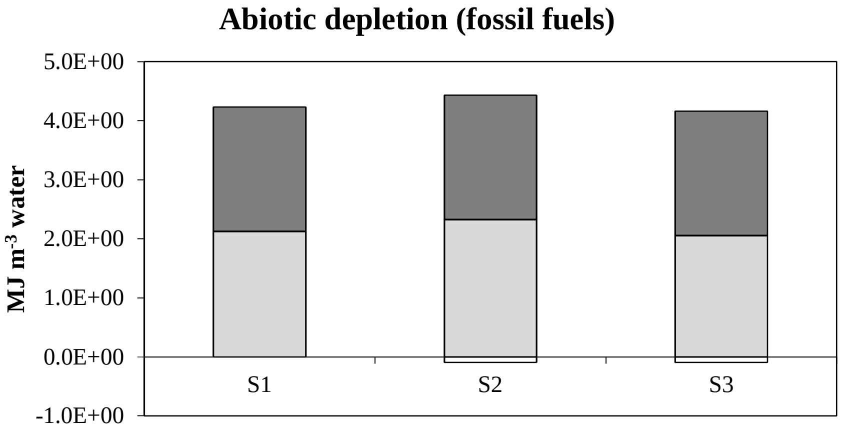
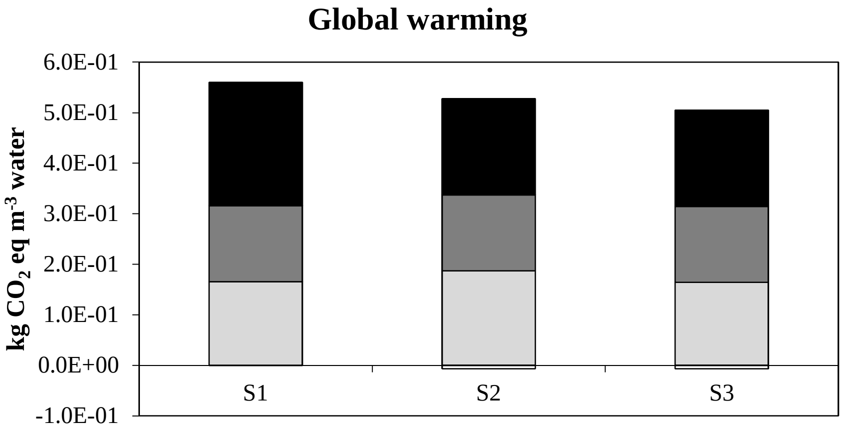
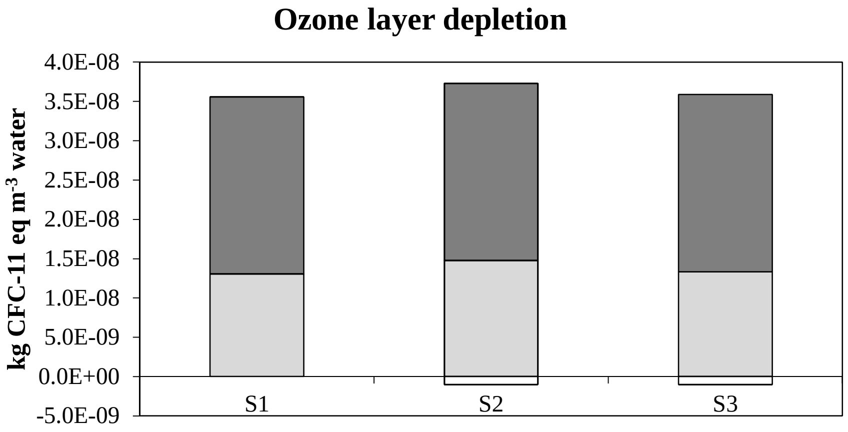


Figure 1. Schematic cross section of CWs for the considered scenarios. S1: conventional CW system (without MFC); S2: CW system coupled with a gravel-based anode MFC; S3: CW system coupled with a graphite-based anode MFC


Abiotic depletion


Abiotic depletion (fossil fuels)


Global warming


Ozone layer depletion

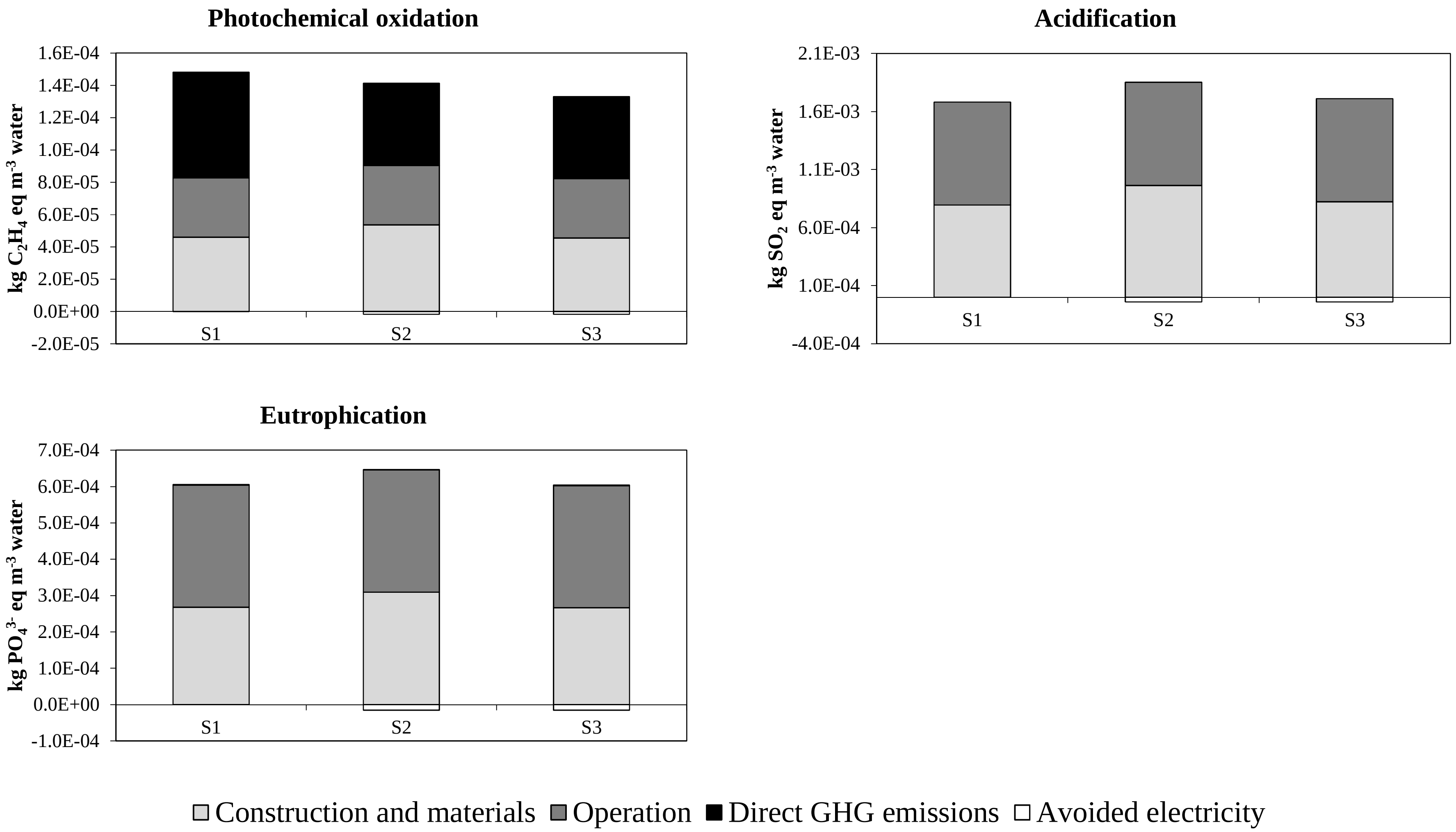


Figure 2. Potential environmental impacts for the three scenarios. Values are referred to the functional unit (1 m^3 of water). S1: conventional CW system (without MFC); S2: CW system coupled with a gravel-based anode MFC; S3: CW system coupled with a graphite-based anode MFC

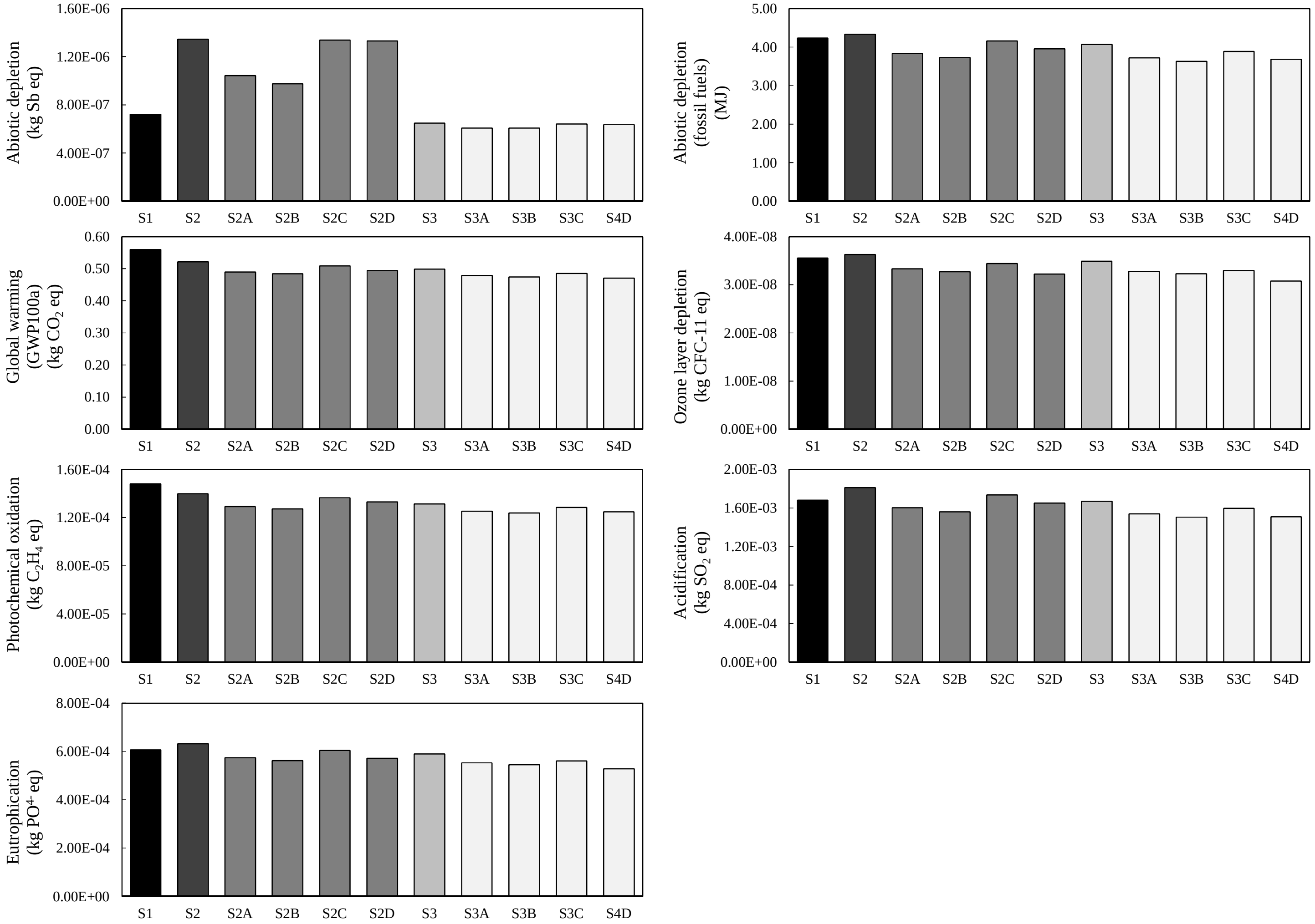


Figure 3. Results of the sensitivity analysis on the potential environmental impacts for the considered scenarios (Scenarios are defined in Table 3). Values are referred to the functional unit (1 m^3 of water).