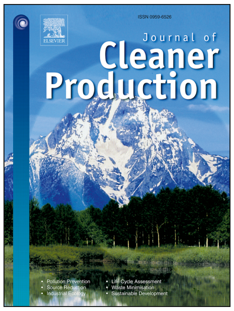

Life Cycle Assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds

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PII: S0959-6526(17)31056-9
DOI: 10.1016/j.jclepro.2017.05.116
Reference: JCLP 9655

To appear in: *Journal of Cleaner Production*

Received Date: 27 January 2017
Revised Date: 3 April 2017
Accepted Date: 21 May 2017

Please cite this article as: Garfí M, Flores L, Ferrer I, Life Cycle Assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds, *Journal of Cleaner Production* (2017), doi: 10.1016/j.jclepro.2017.05.116.

Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high rate algal ponds

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Abstract

The aim of this study was to assess the environmental impact of three alternatives for wastewater treatment in small communities. To this end, a Life Cycle Assessment (LCA) was carried out comparing a conventional wastewater treatment plant (i.e. activated sludge system) with two nature-based technologies (i.e. hybrid constructed wetland and high rate algal pond systems). Moreover, an economic evaluation was also addressed. All systems served a population equivalent of 1,500 p.e. The functional unit was 1 m^3 of water. System boundaries comprised input and output flows of material and energy resources for system construction and operation. The LCA was performed with the software *SimaPro® 8*, using the ReCiPe midpoint method. The results showed that the nature-based solutions were the most environmentally friendly alternatives, while the conventional wastewater treatment plant presented the worst results due to the high electricity and chemicals consumption. Specifically, the potential environmental impact of the conventional wastewater treatment plant was between 2 and 5 times higher than that generated by the nature-based systems depending on the impact category. Even though constructed wetland and high rate algal pond systems presented similar results in terms of environmental impact, the latter showed to be the less expensive alternative. Nevertheless, the constructed wetland system should be preferred when land occupation is of major concern, since it has a smaller footprint compared to the high rate algal pond alternative.

Keywords: Constructed wetlands; Environmental impact assessment; Decentralized wastewater treatment system; High rate algal ponds; Nature-based technology; Wastewater treatment

1. Introduction

Lack of wastewater treatment is one of the major global concerns. Poorly managed wastewater may lead to hazard for human health and the environment. Despite continued efforts have been made to promote the implementation of wastewater treatment systems, around 2,500 million people in the world are still without access to improved sanitation (WHO and UN-Water, 2014). The lack of adequate wastewater treatment is commonly much higher in rural and small communities (<10,000 p.e.) (WHO and UN-Water, 2014). Small agglomerations are generally characterized by limited financial resources, low level of technical expertise and limited access to existing advanced technologies.

Traditional sanitation strategies consisted of the implementation of sewer collection systems and conventional centralized wastewater treatment plants. Conventional wastewater treatment comprises a combination of physical, chemical, and biological processes and operations to remove solids, organic matter and nutrients from wastewater. The most common configuration includes a primary treatment followed by an activated sludge system. The latter consists of an aeration tank and a secondary settling tank. These systems are costly to build and operate, require skilled personnel for operation and maintenance and high energy consumption (EC, 2001; Massoud et al., 2009).

During the last decades, natural technologies (also known as nature-based technologies) for wastewater treatment have been gaining interest since they are an attractive alternative to conventional treatment systems in small communities (Rozkošný et al., 2014; Yildirim and Topkaya, 2012). Natural treatment technologies use modified natural self-treatment processes that take place in the ground soil, water and wetland environment (Rozkošný et al., 2014). Hence, they are characterized by low energy consumption, simple operation and lower capital and operating costs compared to conventional systems (EC, 2001; Rozkošný et al., 2014).

Among all nature-based technologies for wastewater treatment, constructed wetlands are one of the most common types. They are constructed filtration systems with defined filter material (e.g. gravel and sand) and planted with wetland vegetation (e.g. common reed). In these systems, wastewater flows through the filter material and the treatment is carried out by chemical, physical and biological processes (Rozkošný et al., 2014). The presence of vegetation improves the treatment efficiency, producing an effluent suitable for various reuse applications (e.g. irrigation of non-alimentary crops) (Ávila et al., 2013; Pedescoll et al., 2013). At present, there are several thousand of operating constructed wetlands worldwide, since they are an appropriate technology to treat both municipal and industrial wastewater in many regions with different climate (France, 2010; Garfí et al., 2012; Vymazal, 2005, 2014; Zang et al., 2015).

In the recent years, high rate algal ponds for wastewater treatment have been gaining popularity. These natural systems, are shallow, paddlewheel mixed, raceway ponds where treatment is carried out by a consortium of microalgae and bacteria which assimilate nutrients and degrade organic matter (Craggs et al., 2014; Park et al., 2011). As oxygen is provided by microalgae, aeration is not required and energy consumption is much lower compared to that of a conventional wastewater treatment plant. Nowadays, high rate algal ponds are considered a promising solution to shift the paradigm from wastewater treatment to resources recovery. Indeed, microalgae grown in high rate algal ponds can be harvested and reused to produce biofuels (Craggs et al., 2014; Montingelli et al., 2015; Uggetti et al., 2017).

Even though wastewater treatment plants reduce the environmental impact caused by untreated sewage discharged into water bodies, they have an impact on the environment themselves, by consuming natural resources for construction and operation (Lopsik, 2013). Therefore, not only technical and economic aspects but also environmental criteria must be taken into account for the selection of the most appropriate technology (Molinos-Senantes et al., 2014).

To date, only a limited number of studies compared the environmental impact of nature-based (e.g. constructed wetlands, slow rate infiltration) and conventional (i.e. activated sludge process) technologies for wastewater treatment in small communities. They pointed out that nature-based technologies are the most environmentally friendly wastewater treatment option (Dixon et al., 2013; Fuchs, et al., 2011; Machado et al., 2007; Yildirim et al., 2012). Nevertheless, studies which include the high rate algal ponds among the possible solutions for wastewater treatment in small communities are still missing.

The aim of this paper was to assess the environmental impacts associated with natural and conventional technologies for wastewater treatment in small agglomerations. To this end, a Life Cycle Assessment (LCA) comparing activated sludge, constructed wetland and high rate algal pond systems was carried out. Moreover, an economic evaluation was also addressed.

2. Materials and methods

2.1 Wastewater treatment systems description

The activated sludge system (hereinafter referred as “conventional wastewater treatment plant”), located in Catalonia (Spain), serves a population equivalent of 1,500 p.e. and the flow rate is 292.5 m^3 d^{-1}. After a pre-treatment, wastewater is treated in an activated sludge reactor with extended aeration followed by a secondary settler. From this unit, treated water is disinfected and reused for irrigation. The sludge is conditioned, thickened, and further dewatered on-site using a centrifuge. In this system, the overall biological oxygen demand (BOD_5) and total suspended solids (TSS) removal rate was around 93-98% for both parameters (inlet BOD_5 and TSS concentration of 240 and 280 mg L^{-1}, respectively).

Constructed wetland and high rate algal pond systems were hypothetical wastewater treatment plants designed by an engineering company to serve the same population equivalent and treat the same influent and wastewater flow rate as the conventional wastewater treatment plant. The detailed engineering design of both systems was carried out in order to obtain an effluent quality suitable for reuse and irrigation of non-alimentary crops according to Spanish regulations (i.e. TSS< 35 mg L^{-1}, *E.coli* < 1000 CFU/100mL) (BOE, 2007) as for the conventional wastewater treatment plant.

The constructed wetland system consisted of a primary treatment (i.e. three-chamber septic tank), two vertical flow constructed wetlands operating alternatively, and a horizontal subsurface flow constructed wetland planted with *Phragmites australis*. The wastewater treatment plant design was based on literature (García and Corzo, 2008) and on previous studies carried out in an experimental system located at the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) (Barcelona, Spain). These studies suggested that hybrid constructed wetland systems (i.e. a combination of vertical and horizontal flow constructed wetlands) were an adequate solution for wastewater treatment and reuse in small agglomerations of the Mediterranean region (Ávila et al., 2013, 2016). Indeed, these systems achieved very high values of removal of solids and organic matter (e.g. around 90-93% and 96-97% for BOD_5 and TSS, respectively) (Ávila et al., 2013, 2016).

With regard to the high rate algal pond system, the design parameters were calculated according to Craggs et al. (2014) and considering the experimental results obtained in previous studies carried out in another experimental system located at the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) (García et al., 2006; Gutiérrez, 2016). These studies showed that in the Mediterranean climate zones HRAP systems can produce a final effluent suitable for various reuse applications (e.g. effluent TSS concentration < 35 mg L^{-1}) if a proper design, operation and harvesting method are considered (Gutiérrez, 2016, Craggs et al., 2014). The system considered in this study comprised a three-chamber septic tank, followed by two high rate algal ponds working in parallel. From these units, the wastewater goes through a settler, where algal biomass is harvested and water is clarified.

In both constructed wetland and high rate algal pond systems, primary sludge is thickened and dewatered on-site, while treated water is disinfected and reused for irrigation, as for the conventional wastewater treatment plant. The specific area requirement was 0.6, 3.5 and 6 m^2 $p.e.^{-1}$ for the conventional wastewater treatment plant, constructed wetland and high rate algal pond systems, respectively.

The flow diagrams of the treatment alternatives are shown in Figure 1. Table 1 and 2 show the characteristics and design parameters of the constructed wetland and the high rate algal pond systems.

Please insert Figure 1

Please insert Table 1

Please insert Table 2

2.2 Life Cycle Assessment

LCA is a comprehensive, systematic and standardized procedure for estimating the potential environmental impacts of a product, process or activity using a cradle to grave approach (ISO, 2000; ISO, 2006). LCA is used for choosing between technologies, products or processes, with a similar performance by accounting for the impacts caused by each alternative over its life cycle. It can be also applied to identifying which life stage brings the most significant environmental impacts and establishing baselines for improvement in further research. The environmental impacts are evaluated by identifying and quantifying energy and materials used and wastes released to the environment through the entire life cycle. LCA consists of four main stages: i) goal and scope definition, ii) inventory analysis, iii) impacts assessment and iv) interpretation of the results (ISO, 2006). The following sections describe the specific content of each step.

2.2.1 Goal and scope definition

The goal of this study is to compare the potential environmental impacts associated with three alternatives for wastewater treatment for small communities:

a) activated sludge system with extended aeration (hereinafter referred as “conventional wastewater treatment plant”) (AS);
b) constructed wetland system (CW);
c) high rate algal pond system (HRAP).

As mentioned above, the main function of the systems considered is to treat wastewater and they were designed in order to treat the same influent and wastewater flow rate. For these reasons, the functional unit is 1 m^3 of treated water.

System boundaries comprised input and output flows of material and energy resources for the construction and operation of these systems over a 20-year period

(Garcia and Corzo, 2008, Yildirim and Topkaya, 2012). Demolition and dismantling phases were not considered since the impact would be marginal compared to the overall impact (Lopsik, 2013; Machado et al., 2007). Direct greenhouse gas (GHG) emissions were considered for all scenarios, since they generally have a large impact on climate change impact categories (Fuchs, et al., 2011; Lorenzo-Toja et al., 2016). In all scenarios, inputs and outputs associated with sludge disposal (i.e. incineration) were taken into account. Regarding sludge transportation to incineration facility, an average distance of 30 km was adopted, based on circumstances generally observed in our zone. Downstream processes including treated water and algal biomass reuse were not considered. Indeed, in wastewater treatment systems sized at less than 2,000 p.e. energy and nutrients recovery from biomass and sludge (e.g. through anaerobic digestion) is usually not implemented (EC, 2001, Gallego et al., 2008). Transportation of construction materials was not accounted for, since it is mainly used during construction work and its contribution only represents a minor fraction of the overall impact when materials are produced locally (Fuchs et al., 2011; Lopsik, 2013).

2.2.2 Inventory analysis

Inventory data on systems construction and operation referred to the functional unit (1 m^3 of water) are shown in Table 3 for each scenario.

In the case of the AS scenario, inventory data was provided by the environmental engineering company that designed and implemented the system. With regards to CW and HRAP scenarios, inventory data were based on the detailed engineering designs performed in the frame of this study.

In the case of the AS, direct GHG emissions were estimated considering the emissions rates obtained in a previous LCA of a similar wastewater treatment plant located in Catalonia (Spain) (i.e. 0.17 g_{CO2} m_{water}^{-3} and 0.11 g_{N2O} m_{water}^{-3}, Table 3) (Lavola, 2015). Regarding the CW scenario, GHG emission rates proposed by Corbella and Puigagut (2015), Mander et al. (2008) and Fuchs et al. (2011) were considered (i.e. 992 g_{CO2} m_{water}^{-3}, 10.9 g_{CH4} m_{water}^{-3}, 0.017 g_{N2O} m_{water}^{-3}, Table 3). These studies estimated the direct GHG emissions of constructed wetland systems with similar characteristics (e.g. type of water, configuration) to the scenario considered in this study.

In the HRAP scenario, NH_4^+ volatilization was estimated through Nitrogen mass balance. To this end, outlet Nitrogen concentrations have been estimated considering removal efficiencies and experimental results obtained in a pilot plant of high rate algal ponds implemented at the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) (García et al., 2000; Gutiérrez , 2016).

Background data (i.e. data of materials, chemicals and electricity production, sludge transportation and incineration process) were obtained from the *Ecoinvent 3.1* database (Moreno-Ruiz et al., 2014; Weidema et al., 2013). For all electricity requirements the Spanish electricity mix was used (Red Eléctrica Española, 2016). It is as follows: nuclear 22%; coal 14%; wind 19%; hydro 16%; fuels 11%; cogeneration 10%; solar photovoltaic and thermoelectric 5%; other renewables 1% and waste 1%.

Please insert Table 3

2.2.3 Impact assessment

Potential environmental impacts were calculated using the software *SimaPro® 8* (Pre-sustainability, 2014) and the ReCipe midpoint method (hierarchist approach) (Goedkoop et al., 2009). This analytical tool is in accordance with ISO 14040 standards

(ISO, 2000). Considering the most pressing environmental issues in our zone, the following impact categories were assessed: Metal Depletion, Fossil Depletion, Climate Change, Ozone Depletion, Terrestrial Acidification, Freshwater Eutrophication and Marine Eutrophication. In the present study only the mandatory phases of impacts assessment (classification and characterisation) defined by the ISO standard (ISO, 2006) were conducted.

2.3 Sensitivity analysis

A sensitivity analysis was performed by modifying the most relevant assumptions of the wastewater treatment alternatives to evaluate how the uncertainty on inventory data may influence the results. Hence, the following parameters were considered: N_2O emissions in the AS and CW scenarios; CH_4 emissions in the CW scenario, and NH_3 emissions in the HRAP scenario. CO_2 direct emissions were not included in the sensitivity analysis, since CO_2 from biogenic sources does not contribute to Climate Change Potential (Doorn et al., 2006). It has to be mentioned that N_2O and CH_4 direct emissions in AS and CW scenarios only affect the Climate Change Potential; on the other hands NH_3 emissions in HRAP scenario only influence Terrestrial Acidification and Marine Eutrophication Potentials. A variation of ± 10% was considered for all parameters and the sensitivity coefficient was calculated using Eq. (1) (Dixon et al., 2003):

$$\text{Sensitivity Coefficient (S)} = \frac{(\text{Output}_{\text{high}} - \text{Output}_{\text{low}})/\text{Output}_{\text{default}}}{(\text{Input}_{\text{high}} - \text{Input}_{\text{low}})/\text{Input}_{\text{default}}} \qquad (1)$$

where Input is the value of the input variable (i.e. N_2O, CH_4 and NH_3 emissions) and Output is the value of the environmental indicator (i.e. Climate Change, Terrestrial Acidification and Marine Eutrophication Potentials).

2.4 Economic assessment

The economic assessment was carried out comparing the capital cost and the operation and maintenance cost of each wastewater treatment alternative. In all scenarios, data were gathered from the detailed engineering design and prices were provided by local companies. The capital cost included the cost for earthmoving, construction materials purchase and electrical works. The operation and maintenance cost comprised costs associated to labour, electricity, purchase of chemicals (i.e. consumables), sludge disposal, and ordinary and extraordinary maintenance (e.g. equipment replacement). For all scenarios, a lifespan of 20 years was considered.

3. Results and discussion

3.1 Life Cycle Assessment

Figure 2 depicts the potential environmental impacts associated with each wastewater treatment alternative.

The conventional wastewater treatment plant (scenario AS) dominated in all impact categories analysed, while the constructed wetland and the high rate algal pond systems (scenarios CW and HRAP, respectively) showed a similar environmental performance. In fact, the environmental impacts of the conventional wastewater treatment plant (scenario AS) were between 2 and 5 times higher than those of the nature-based technologies (scenarios CW and HRAP) for the considered impact categories. This was mainly due to the high electricity and chemicals consumption for the operation of the conventional wastewater treatment plant (Table 3). Similar results were obtained by previous studies which compared the potential environmental impacts of activated sludge and constructed wetland systems (Dixon et al., 2003; Machado et al., 2007; Yildirim et al., 2012).

In the case of the AS scenario, the major impact was due to the operation phase (from 85 to 97% of the total impact in all indicators), while the construction phase accounted for less than 12% of the total impact in all indicators. Previous studies showed that, in all considered impact categories the operation phase contribution to the overall impact ranged between 30 and 95% depending on the size of the conventional wastewater treatment plant (from 500 to 680,000 p.e.) (Gallego et al., 2008; Lopsik, 2013; Lorenzo-Toja et al., 2016; Machado et al., 2007; Piao, et al., Yildirim and Topkaya, 2012). Moreover, it was observed that the smaller the size of the conventional wastewater treatment plants, the higher the electricity consumption per cubic meter of treated water (Lorenzo-Toja et al., 2015). In this study, the high electricity consumption (1.26 kWh m^{-3}) was the main responsible for the low environmental performance of the conventional wastewater treatment plant. These facts suggest that the smaller the size of the community, the more appropriate the nature-based solutions are, if compared to conventional wastewater treatment systems.

In the case of the CW and HRAP scenarios, the life cycle was influenced by both the construction and operation phases. In regards to Fossil Depletion, Ozone Depletion, Terrestrial Acidification, Freshwater Eutrophication and Marine Eutrophication Potentials, the contribution of the construction and operation stages accounted for 25-35% and 35-65% of the total impact, respectively. On the other hand, Metal Depletion Potential was mainly affected by the construction phase (60-65% of the overall impact). Metal Depletion Potential strongly depends on non-renewable resources required during the overall life cycle. Since nature-based technologies have low raw materials requirements for their operation, the major impact was caused by resources consumption for the systems construction. Moreover, it has to be noted that the Metal Depletion Potential generated by the AS scenario was only 2 times higher than that caused by the CW and HRAP scenarios. Indeed, despite nature-based systems for wastewater treatment comprise low-tech and low-energy processes, they require a large amount of raw material for their implementation (Table 3). It is due to the large land required for natural wastewater treatment systems to achieve the desired treatment efficiency (0.6, 3.5, 6 m^2 $p.e.^{-1}$ for the AS, CW and HRAP scenarios, respectively). This is in accordance with previous studies which observed that, in the case of constructed wetlands, the life stage with the greatest overall impact was the construction (Dixon et al., 2003; Fuchs et al., 2011; Machado et al., 2007). These authors also suggested that the construction impacts could significantly increase if materials for nature-based systems implementation were transported from a long distance or if systems and equipment had shorter operation lifetime than that estimated. With regards to the Climate Change Potential, construction and operation accounted for around 50% of the overall impact in the HRAP scenario. In the CW scenario, direct GHG emissions, construction and operation phases contributed equally to the overall impact. This fact highlighted the necessity of including gaseous emissions from the wastewater treatment process, as suggested by previous research (Corbella et al., 2017; Corominas et al., 2013; Fuchs et al., 2011). Finally, in all scenarios sludge transportation and disposal had a slight impact (<5% of the total impact) on all considered impact categories, except for the Freshwater Eutrophication and Marine Eutrophication Potentials in which it accounted for around 15-20% of the overall impact.

Please insert Figure 2

3.2 Sensitivity analysis

Table 4 shows the results of the sensitivity analysis. As mentioned above, N_2O and CH_4 direct emissions in AS and CW scenarios only affect the Climate Change Potential; on the other hands NH_3 direct emissions in HRAP scenario only influence Terrestrial Acidification and Marine Eutrophication Potentials.

With regard to N_2O direct emissions in AS and CW scenarios, the results showed that Climate Change Potential was not sensitive to this parameter (sensitivity coefficient = 0.02 and 0.007 for AS and CW scenarios, respectively). This means that a 10% increase in N_2O direct emissions would increase this environmental indicator by 0.2% and 0.07% in AS and CW scenarios, respectively.

The Climate Change Potential showed to be sensitive to CH_4 emissions in CW scenario (sensitivity coefficient = 0.35). Indeed, a 10% increase in CH_4 emissions in CW scenario would increase Climate Change Potential by 3.5%.

Regarding to NH_3 emissions in HRAP scenario, the Terrestrial Acidification and Marine Eutrophication Potentials showed to be somewhat sensitive to this parameter (sensitivity coefficient = 0.15 for both environmental indicators). Indeed, a 10% increase of this parameter would increase these indicators by 1.5%.

In conclusion, the results were found to be sensitive to CH_4 direct emissions in CW scenario. However, since it affects only one of the impact categories considered (i.e. Climate Change Potential), it can be concluded that the main findings of this study are not strongly dependent on the assumptions considered.

Please insert Table 4

3.3 Economic assessment

Table 5 shows the results of the economic analysis. With regard to capital costs, the high rate algal pond system (scenario HRAP) appeared as the less expensive alternative, followed by constructed wetland (scenario CW) and conventional wastewater treatment (scenario AS) systems (Table 5). The AS alternative also presented the highest operation and maintenance cost. Moreover, the CW scenario showed a slightly lower operation and maintenance cost compared to the HRAP scenario. It was in accordance with the results obtained by Molinos-Senante et al. (2014), who carried out a sustainability analysis comparing conventional and nature-based technologies (e.g. activated sludge, constructed wetland, open ponds) for wastewater treatment in small communities (1,500 p.e.).

The lower capital cost of the HRAP scenario might be mainly attributed to the easier construction and to the lower amount of materials needed compared to the CW and AS scenarios (Table 3). On the other hand, the higher operation and maintenance cost in AS and HRAP scenarios was mainly due to the higher electricity consumption (Table 3). Indeed, the energy consumption is a major contributor to the operational and maintenance cost of small scale wastewater treatment plants (<10,000 p.e.) (Gallego et al., 2008, Tsagarakis et al., 2003).

On the whole, the conventional wastewater treatment system showed to be between 2 and 3 times more expensive than the nature-based technologies.

Please insert Table 5

3.4 Potential benefits of implementing nature-based solutions for wastewater treatment in small communities

In accordance with the results obtained in this study, around 0.6 and 1.3 kg_{CO2} m^{-3} are generated by the construction and the operation of nature-based and conventional wastewater treatment systems, respectively (Figure 2). This means that, some 45 kg_{CO2eq} $p.e.^{-1}$ $year^{-1}$ could be saved by implementing nature-based solutions instead of conventional wastewater treatment plants (Table 6). In terms of costs, nature-based solutions implementation would save around 350 € p.e.$^{-1}$ per system construction and 25 € p.e.$^{-1}$ year^{-1} (Table 5).

Nevertheless, systems footprint should be taken into account when land occupation is of major concern. Among nature-based technologies, constructed wetlands are the alternative which requires less land. Indeed, a specific area lower than 2 m^2 p.e.$^{-1}$ is adequate for hybrid systems implemented in warm climate regions (Ávila et al., 2016). Still, conventional wastewater treatment systems have significantly lower footprint compared to all nature-based solutions (<1 m^2 p.e.$^{-1}$ vs. 2-6 m^2 p.e.$^{-1}$, respectively) (EC, 2001; Garcia and Corzo, 2008).

Please insert Table 6

4. Conclusions

In this study, an LCA was carried out in order to compare three alternatives for wastewater treatment in small communities. Results showed that the potential environmental impact of the conventional wastewater treatment plant (i.e. activated sludge system) was between 2 and 5 times higher than that generated by the nature-based systems, depending on the impact category. In particular, the constructed wetland and the high rate algal pond systems presented similar environmental performance.

In terms of costs, the conventional wastewater treatment system showed to be between 2 and 3 times more expensive than the nature-based technologies. Specifically, high rate algal pond system appeared as the less expensive alternative, being the most suitable solution from an economic point of view.

On the other hand, constructed wetland system is more appropriate when the land occupation is of major concern, since it has a smaller footprint compared to the high rate algal pond alternative (3.5 vs. 6 m^2 $p.e.^{-1}$, respectively).

Finally, constructed wetland and high rate algal pond systems are appropriate solutions for wastewater treatment in small agglomerations, which may help to reduce environmental impacts and costs associated with wastewater treatment. These facts partially offset the high specific area required for their implementation compared to conventional wastewater treatment plants.

Regarding the future research needs, an environmental and economic analysis of full-scale systems should be carried out using data obtained during a long-term monitoring (e.g. systems lifespan, wastewater treatment efficiency, GHG emissions).

Acknowledgements

This research was funded by the Spanish Ministry of Economy and Competitiveness (FOTOBIOGAS CTQ2014-57293-C3-3-R). Marianna Garfí is grateful to Ministry of Economy and Competitiveness (Spain) (Plan Nacional de I+D+i 2008-2011, Subprograma Juan de la Cierva (JDC) 2012). Authors are also grateful to Anna Cullell and Julia Hereza for their contribution to this study.

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573 **Table 1.** Constructed wetland system characteristics and design parameters

System characteristics	*Unit*	
Inlet BOD_5 concentration	$mg_{BOD}\ L^{-1}$	240
Inlet TSS concentration	$mg_{TSS}\ L^{-1}$	280
Outlet BOD_5 concentration	$mg_{BOD}\ L^{-1}$	<25
Outlet TSS concentration	$mg_{TSS}\ L^{-1}$	<15
Flow rate	$m^3\ d^{-1}$	292.5
Average daily wastewater flow rate	$m^{-3}\ p.e.^{-1}\ d^{-1}$	0.20
Population equivalent	*p.e.*	1,500
Total surface area	m^2	5,350
Specific area requirement	$m^2\ p.e.^{-1}$	3.5
Design parameters	*Unit*	
Organic Loading Rate (OLR)*	$g_{BOD}\ m^{-2}\ d^{-1}$	20
Hydraulic Retention Time (HRT)	*d*	5
Vertical constructed wetlands		
Number of vertical constructed wetland cells	-	2
Constructed wetland cell dimensions	*m (D×L×W)*	0.8 × 125 × 15
Horizontal constructed wetland		
Number of horizontal constructed wetland cells	-	1
Constructed wetland cell dimensions	*m (D×L×W)*	0.6 × 40 × 19

574

575

Table 2. High rate algal pond system characteristics and design parameters

System characteristics	*Unit*	
Inlet BOD$_5$ concentration	$mg_{BOD}\ L^{-1}$	240
Inlet TSS concentration	$mg_{TS}\ L^{-1}$	280
Outlet BOD$_5$ concentration	$mg_{BOD}\ L^{-1}$	<25
Outlet TSS concentration	$mg_{TSS}\ L^{-1}$	<35
Flow rate	$m^3\ d^{-1}$	292.5
Average daily wastewater flow rate	$m^{-3}\ p.e.^{-1}\ d^{-1}$	0.20
Population equivalent	*p.e.*	1,500
Total surface area	m^2	9,000
Specific area requirement	$m^2\ p.e.^{-1}$	6
Design parameters	*Unit*	
Organic Loading Rate (OLR)	$g_{BOD}\ m^{-2}\ d^{-1}$	6.5
Hydraulic Retention Time (HRT)	*d*	6
Number of ponds	-	2
Channel width	*m*	10
Channel length	*m*	375

Table 3 Summary of wastewater treatment inventory for scenarios AS, CW and HRAP. Values are referred to the functional unit (1 m^3 of water).

Inputs	**Unit**	**AS**	**CW**	**HRAP**
Construction materials				
Concrete and cement	m^3 m^{-3}	3.11E-02	1.13E-04	3.49E-04
Metals	kg m^{-3}	9.72E-03	2.43E-02	3.57E-02
Coating (Bituminous coating and basalt)	kg m^{-3}	9.12E-02	4.73E-03	4.55E-03
Plastics	kg m^{-3}	8.30E-04	2.80E-03	7.89E-05
Gravel and sand	kg m^{-3}	7.19E-02	7.82E-01	-
Bricks	kg m^{-3}	-	1.66E-02	-
Glass fibre	kg m^{-3}	-	-	1.37E-04
Operation				
Chlorine dioxide	g m^{-3}	1.20E+1	1.20E+1	1.20E+1
Polyelectrolyte	kg m^{-3}	9.57E-04	1.53E-06	1.53E-06
Coagulant	kg m^{-3}	1.13E-01	-	-
Electricity	kWh m^{-3}	1.26E+00	2.20E-01	2.50E-01
Outputs				
Waste				
Sludge	kg m^{-3}	1.35E-01	3.45E-01	3.45E-01
Emissions to air (direct emissions)				
CO_2	g m^{-3}	1.70E-1	9.92E+2	-
CH_4	g m^{-3}	-	1.09E+1	-
N_2O	g m^{-3}	1.10E-01	1.69E-02	-
NH_3	g m^{-3}	-	-	3.30E-1

Scenarios: AS: conventional wastewater treatment plant; CW: constructed wetland system; HRAP: high rate algal pond system.

Table 4. Results of the sensitivity analysis for the considered parameters: N_2O direct emissions in the AS and CW scenarios; CH_4 direct emissions in the CW scenario, and NH_3 direct emissions in the HRAP scenario.

		Impact categories		
Parameters	**g m^{-3} water**	**Climate change** **kg CO_2 eq m^{-3} water**	**Terrestrial acidification** **kg SO_2 eq m^{-3} water**	**Marine eutrophication** **kg N eq m^{-3} water**
N_2O emissions (scenario AS)	0.099	1.27E+00	-	-
	0.110 (base case)	1.27E+00	-	-
	0.121	1.28E+00	-	-
CH_4 emissions (scenario CW)	9.810	6.67E-01	-	-
	10.900 (base case)	6.92E-01	-	-
	11.990	7.16E-01	-	-
N_2O emissions (scenario CW)	0.015	6.91E-01	-	-
	0.017 (base case)	6.92E-01	-	-
	0.019	6.92E-01	-	-
NH_3 emissions (scenario HRAP)	0.297	-	3.92E-03	1.18E-04
	0.330 (base case)	-	4.00E-03	1.21E-04
	0.363	-	4.08E-03	1.24E-04

Scenarios: AS: conventional wastewater treatment plant; CW: constructed wetland system; HRAP: high rate algal pond system.

Table 5. Capital, operation and maintenance costs and cost saving due to the implementation of CW and HRAP vs. AS.

	Unit	**AS**	**CW**	**HRAP**
Capital cost	€ p.e.$^{-1}$	540.93	210.36	164.14
Operation and maintenance cost	€ m^{-3}	0.79	0.40	0.42
Capital cost reduction	€ p.e.$^{-1}$	-	330.57	376.79
Operation and maintenance cost reduction	€ m^{-3}	-	0.39	0.37
	€ p.e.$^{-1}$ year^{-1}	-	27.76	26.33

Scenarios: AS: conventional wastewater treatment plant; CW: constructed wetland system; HRAP: high rate algal pond system.

Table 6. CO_2 emissions saving due to the implementation of CW and HRAP vs. AS.

	Unit	**AS**	**CW**	**HRAP**
CO_2 emissions	$kg_{CO2\ eq}\ m^{-3}$	1.27	0.69	0.57
	$kg_{CO2\ eq}\ p.e.^{-1}\ d^{-1}$	0.25	0.13	0.11
CO_2 emissions reduction	$kg_{CO2\ eq}\ p.e.^{-1}\ d^{-1}$	-	0.11	0.14
	$kg_{CO2\ eq}\ p.e.^{-1}\ year^{-1}$	-	41.36	50.22

Scenarios: AS: conventional wastewater treatment plant; CW: constructed wetland system; HRAP: high rate algal pond system.

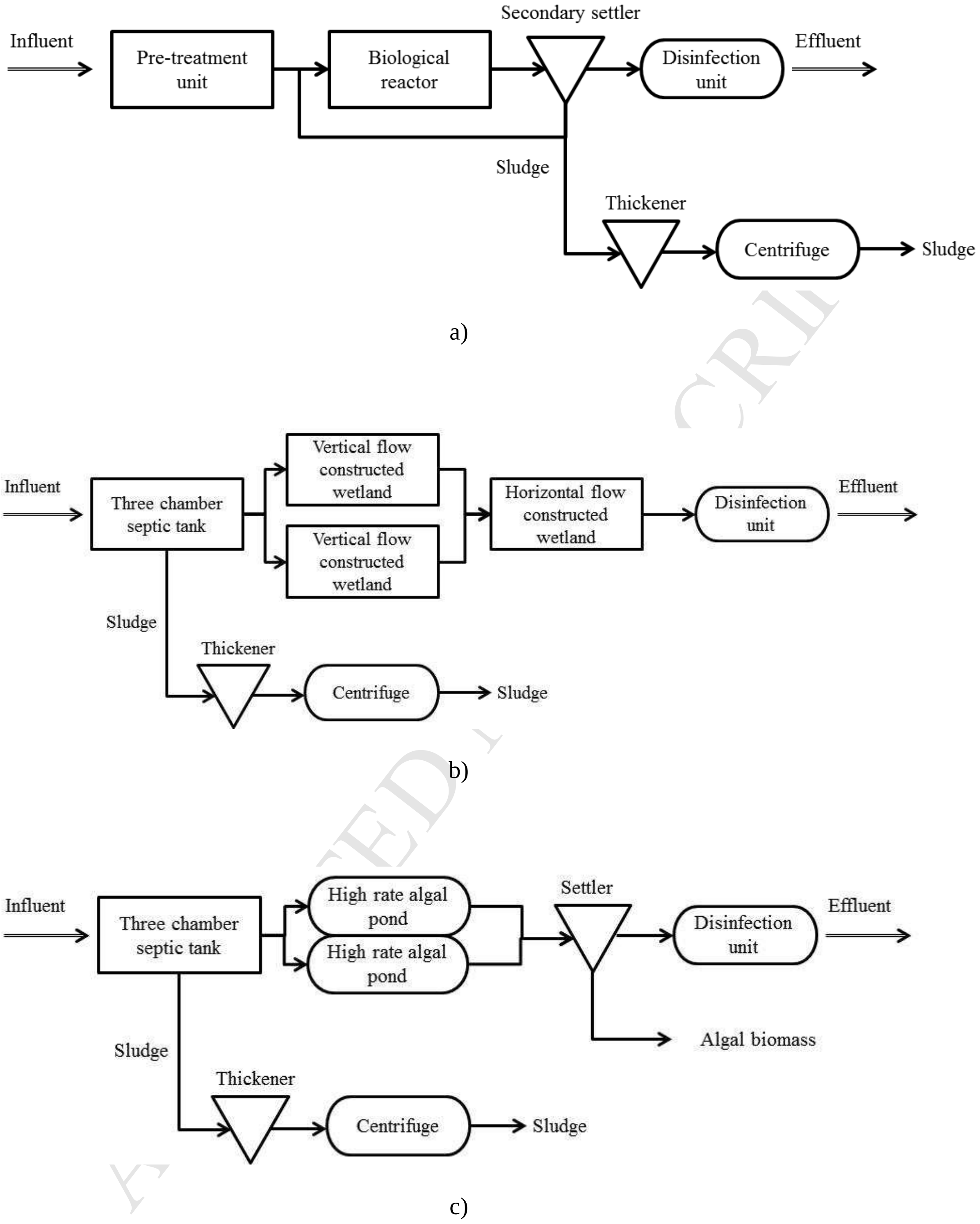
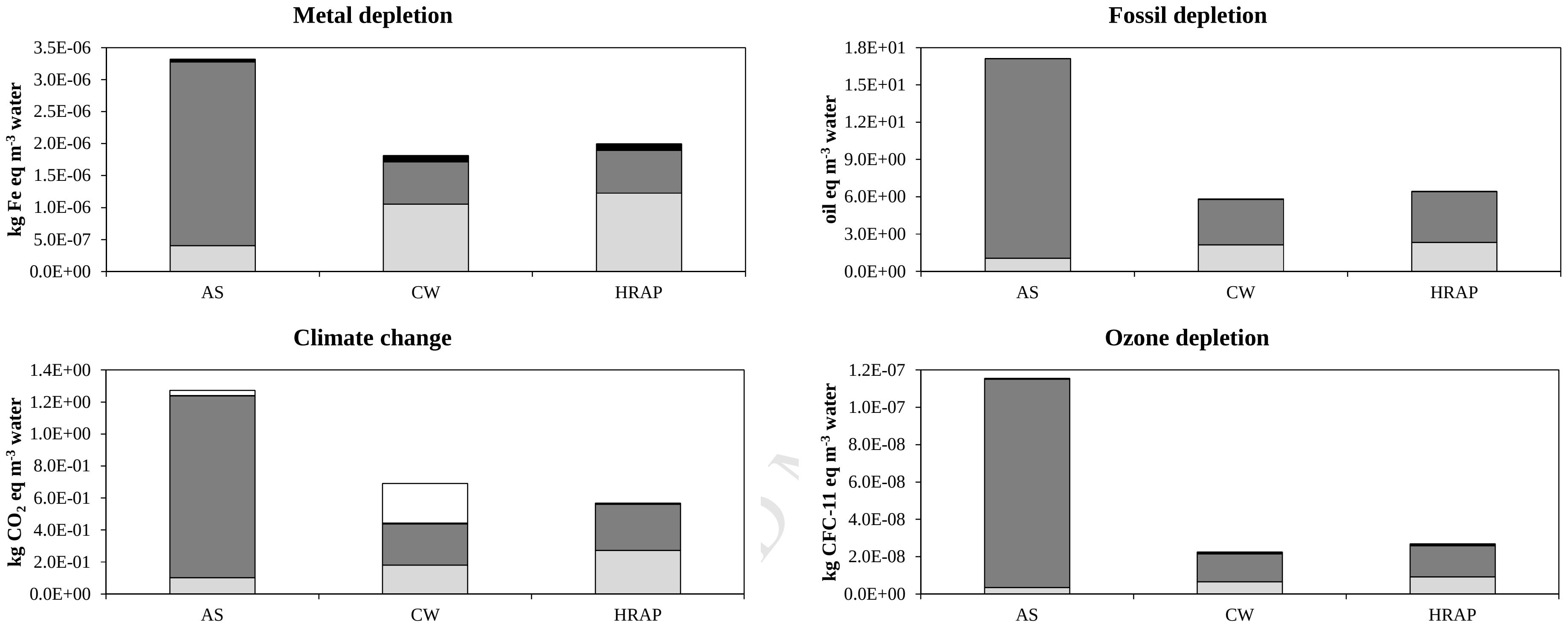


Figure 1. Flow diagrams of the treatment alternatives: a) conventional wastewater treatment plant (AS); b) constructed wetland system (CW); c) high rate algal pond system (HRAP)


Metal depletion
kg Fe eq m^{-3} water
3.5E-06
3.0E-06
2.5E-06
2.0E-06
1.5E-06
1.0E-06
5.0E-07
0.0E+00
AS
CW
HRAP
Fossil depletion
oil eq m^{-3} water
1.8E+01
1.5E+01
1.2E+01
9.0E+00
6.0E+00
3.0E+00
0.0E+00
AS
CW
HRAP
Climate change
kg CO$_2$ eq m^{-3} water
1.4E+00
1.2E+00
1.0E+00
8.0E-01
6.0E-01
4.0E-01
2.0E-01
0.0E+00
AS
CW
HRAP
Ozone depletion
kg CFC-11 eq m^{-3} water
1.2E-07
1.0E-07
8.0E-08
6.0E-08
4.0E-08
2.0E-08
0.0E+00
AS
CW
HRAP

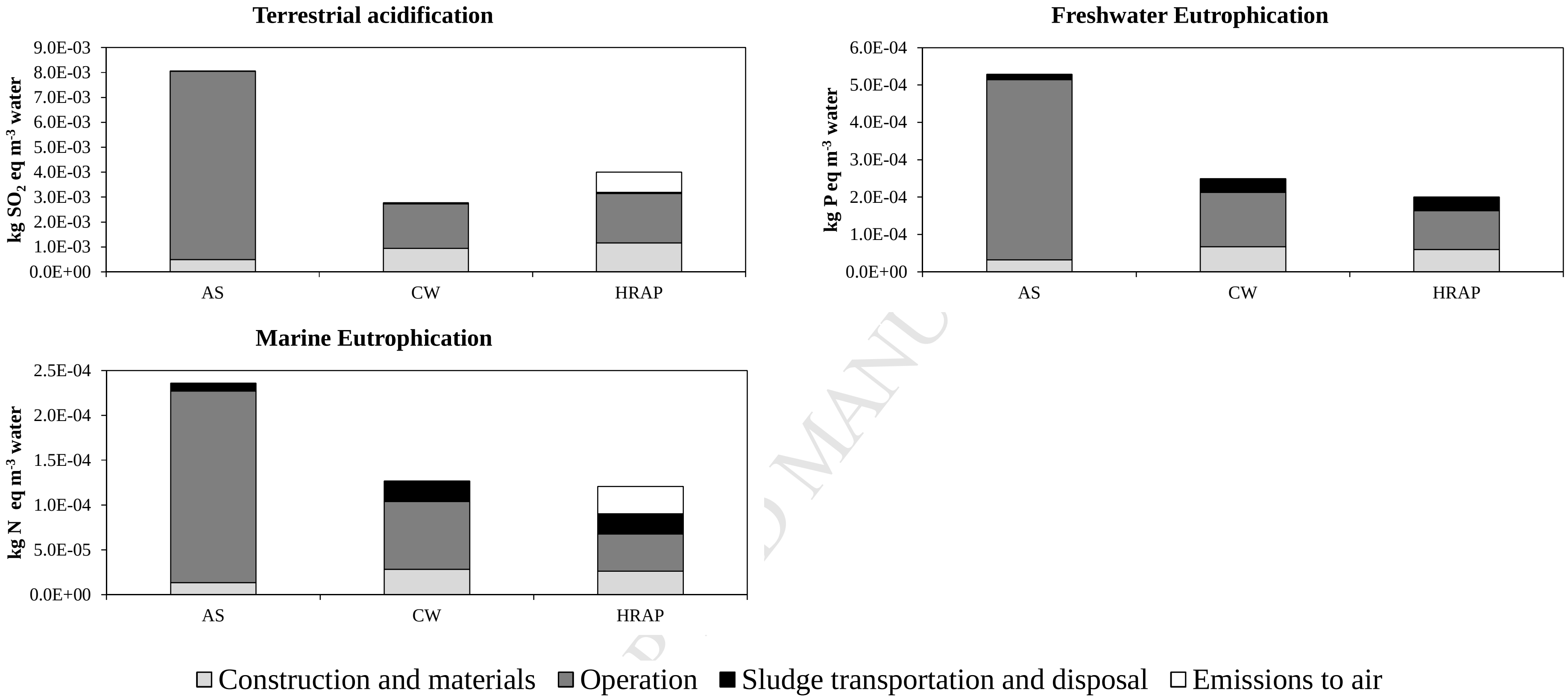


Figure 2. Potential environmental impacts for the three wastewater treatment alternatives. Values are referred to the functional unit (1 m^3 of water).

Scenarios: AS: conventional wastewater treatment plant; CW: constructed wetland system; HRAP: high rate algal pond system.