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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 1500 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.

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 2500 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).

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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-Senante 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., 2003; Fuchs et al., 2011; Machado et al., 2007; Yildirim and Topkaya, 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 1500 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/100 mL) (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 Fig. 1. Tables 1 and 2 show the characteristics and design parameters of the constructed wetland and the high rate algal pond systems.

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 identify which life stage brings the most significant environmental impacts and establish baselines for improvement in