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Life cycle assessment of integrated wastewater treatment systems with constructed wetlands in rural areas

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Studies identifying treatment technologies that combine low costs, high efficiencies, and lower environmental impacts are of great value. Thus, the present study investigated the performance of a wastewater treatment system located on a rural property by life cycle assessment. The system consisted of an anaerobic unit (upflow anaerobic sludge blanket combined with an anaerobic filter), four subsurface flow constructed wetlands, and two photoreactors. The reductions in chemical oxygen demand varied between 93% and 97%, whereas the biochemical oxygen demand decreased by 97–98%. Additionally, 97% of the total Kjedahl nitrogen, 100% of the ammoniacal nitrogen, and more than 90% of total phosphorus were removed from the wastewater. These data were used with reference to the life cycle inventory. The results obtained by the analysis of the endpoint H inventory network showed that 67.3% of the environmental impacts were related to the construction while 32.7% were associated to the operation of the system. The phototreament (45%) and anaerobic (36%) units were responsible for the highest environmental burdens of the constructions phase. By considering the operation of the system with a lifespan of 10 years, again the anaerobic unit accounted for most of the environmental impacts, mainly related to climate change. However, the system presents several potentialities, which might turn it, more environmental friendly and life cycle assessment showed that some of them such as energy recovery from the anaerobic unit will greatly reduce the environmental pressure indexes. Thus, the present study showed that the application of a life cycle assessment can give valuable insights for setting the best configurations for a wastewater treatment system in rural areas by identifying the most critical parameters and by the evaluation of actions which might reduce the environmental impacts.

1. Introduction

All over the world, there is a growing concern about water scarcity. The increase in world's population and consequently the higher pollution levels related with this growth, will lead to dramatic scenarios regarding drinking water availability in many countries. According to a report from the World Health Organization (WHO) almost 750 million people have no access to potable drinking-water and around 1.8 billion people use a source of drinking-water that is faecally contaminated (WHO/UNICEF, 2015). Moreover, it is also estimated that 2.5 billion people lack access to improved sanitation, being responsible for many diseases and millions of deaths worldwide. So, the establishment of appropriate water and wastewater management systems is a vital issue, especially in developing countries (Lam et al., 2015). Sanitation data from these countries reveal serious hygiene, health, economic and social implications that highlight the urgent need to develop less expensive, more efficient and easy-to-maintain technologies which may suit regional realities (Kadlec and Knight, 1996; Philippi and Sezerino, 2004).

In this sense, the need to reuse wastewater in developing countries has received growing attention once water shortage continues to increase in many regions. In Brazil, most of the traditional and decentralized processes for domestic sewage treatment include septic tank and drain field, and more recently, the combination of septic tank and anaerobic filter (Horn et al., 2014).

When considering sanitation in Brazilian rural areas, the problems linked with wastewater treatment are primarily related to the lack and/or stagnation of “cesspit”, hole, well, or septic tank/swallow-hole systems. Additionally, in most properties with septic tank/swallow-hole systems, the location (proximity to water

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bodies and groundwater) is not regulated, and the construction of these systems rarely follows specified guidelines. Guidelines are available in brochures and newsletters prepared by the technical staff of many municipalities and contain recommendations concerning septic tank, anaerobic filter, and swallow-hole systems (Massoud et al., 2009). Only a few studies have investigated the reuse of wastewater in rural areas, limiting the application of wastewater treatment because of the technical adjustments required to improve the efficiency of the treatment system. Further researches focusing in treatment techniques are needed to develop effective, practical, and economical processes, which might have a good reception and evaluation by farmers.

The main pollutants and contaminants of wastewater in rural areas are colloidal material (suspended aluminosilicate), organic matter, pathogenic agents originating from both domestic sewage and improperly treated animal waste, pesticides and fertilizers used on crops as well as pharmaceutical active compounds (PhCAs) (Basílico et al., 2013; Li et al., 2013; Wang et al., 2011). Traditional treatment methods such as phase separation, filtration/adsorption, anaerobiosis, and microbiological mixed systems can be used to eliminate colloids, organic matter, fertilizers and pathogenic agents from wastewater. However, these methods are unable to fully remove micropollutants like pesticides, hormones, and PhCAs that are dissolved in the water, even by treatment processes adopted by public water suppliers. Decantation, filtration, and disinfection processes are used sequentially for treating the water but can also be applied to the reuse of pretreated wastewater (Saeed and Sun, 2012).

In addition to the need to implement systems that provide sanitation in rural areas, the environmental effects of these processes should be considered. To date, a small number of studies have investigated the sustainable configuration of these systems in developing countries, with a particular lack of research on direct environmental pressure indexes and life cycle assessments (LCAs) (Zhang et al., 2010; Yıldırım and Topkaya, 2012). Many researchers have considered LCA analysis the best practice regarding the assessment of the environmental aspects and possible impacts of a complex group of processes such as those of wastewater treatment plants or urban water cycles (Pintilie et al., 2016).

In Europe, several studies have used LCA as a tool to evaluate the sustainability of sanitation systems in rural areas, including the studies developed by Machado et al. (2007), Lopsik (2013) and Maffey et al. (2013). Such investigations often make comparisons between non-intensive energy systems and the potential for recovery of nutrients and biomass. However, as already mentioned, very few LCAs of wastewater management systems have been conducted in developing countries. According to Lam et al. (2015) the assessment of wastewater management in developing countries is important, especially for rural areas where sanitation conditions are usually poor.

Constructed wetlands (CWs) for wastewater treatment constitute an interesting low-cost alternative for application in developing countries, such as Brazil, particularly for sanitation in small rural communities (Kivaisi, 2001; Vymazal and Kröpfelová, 2009). The use of CWs for primary, secondary, and tertiary treatment provides satisfactory treatment of pollutants, such as organic matter and recycling nutrients, improving the quality of the treated wastewater (Maine et al., 2013; Sezerino, 2006; Zhang et al., 2012). Nevertheless, despite the environmental benefits arising from the application of CWs, pollutant load factors for total Kjeldahl nitrogen (TKN) and total phosphorus (P) have surface area requirements that may preclude the use of these systems (Horn et al., 2014). Thus, the combined use of CWs with a pre-treatment in order to reduce load factors and with a post-treatment to make a final polishing of the wastewaters might represent an interesting sanitation system for application in rural areas.

The system adopted in the present work was operated and received configuration changes to provide a semi-closed circuit of gray and black wastewater in a rural property located in the Rio Pardo Valley of southern Brazil. This wastewater treatment system is composed of an upflow anaerobic sludge blanket combined with an anaerobic filter (UASB/BF), subsurface constructed wetlands (SSFCWs), and disinfection reactors that use ultraviolet (UV-254 nm) radiation. The general objective of this design (UASB/BF + SSFCWs + UV) was to establish alternatives to improve sanitation considering sustainability studies based on LCA in the specific rural regions participating in this study with potential investments by the National Water Agency (ANA) and to provide a treatment technology for wastewaters generated in rural properties.

2. Methodology

2.1. Configuration of the UASB/BF + SSFCWs + UV system

Fig. 1 presents the wastewater treatment unit (WWTU). This experimental system was designed to develop a decentralized model aiming to reuse the treated wastewater in each property. The choice of an individual WWTU for each property is justified by the low occupation density in the rural area. The system comprises a grease trap, an UASB/BF unit, four SSFCWs disposed sequentially and a photo treatment unit with two photoreactors. The wastewaters used in the present research were composed by gray and blackwaters generated at a rural property. Initially, the graywaters were treated at the grease trap and then flow to the UASB/BF, where were mixed with blackwaters directly disposed in the unit. After a hydraulic retention time (HRT) of 24.4 h, the wastewaters were conveyed to the SSFCWs sub-units and stay there for 9 days. Finally, a centrifugal pump (using solar power as a source of renewable energy) pumped the wastewaters to the photo treatment unit, where they are irradiated and so making them ready to be reused in the flushing toilets. The system received a diary wastewater inflow of 0.6 m^3 and had a total HRT of 10.2 days.

The UASB and BF used in this study were composed of fiberglass and had volumes of 400 and 210 L, respectively. The BF reactor was filled with #4 gravel (diameter of 64–100 mm). The gas generated in the anaerobic process was drained through a 24-mm polyvinyl chloride (PVC) pipe with a dissipation height of 6 m. The CWs were arranged to have a subsurface horizontal flow. Four sequential wetland beds were constructed in the soil using a 1.6-mm-thick high-density polyethylene (HDPE) sealing membrane. The filter support medium was composed of a 30-cm layer of #4 gravel (64–100 mm) and overlapped by a layer of 30-cm #1 gravel (20–40 mm). The hydraulic equipment used in the distribution and collection areas consisted of perforated PVC pipes and flanges with a diameter of 40 mm.

Hymenachne grumosa (Nees) Zu was selected as the macrophyte in our study because of its desirable characteristics for wetland-based water treatment, such as easy acclimatization to the study site, supporting load factors of total P of at least 0.3 g m^{-1} day^{-1}, to have a root system of at least 40 cm in length and allow the pruning every three or four months (Machado et al., 2015).

The size of the wetland was based on organic loading and on results from previous studies, which indicated a range of 3–5 m^2 per person (Calijuri et al., 2009; Sousa et al., 2004; Vymazal, 2005). The study conducted by Sousa et al. (2004) was consulted for the design of the present system, because the applied load of COD in that study ranged from 5.01 to 9.45 g COD $m^{-2}day^{-1}$.

A summary of the main characteristics of the SSFCWs is listed in Table 1. For the disinfection assays, two PVC photoreactors with a