Ecological Engineering 103 (2017) 217–225

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Resource efficient wastewater treatment in a developing area—Climate change impacts and economic feasibility

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ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form 14 March 2017
Accepted 2 April 2017
Available online 12 April 2017

Keywords:
Wastewater treatment
Constructed wetlands
LCA

ABSTRACT

Resource efficiency in wastewater treatment (WWT) is widely needed, not least in developing areas. Natural, less capital intensive processes in wastewater purification may offer developing economies an alternative to traditional biological processes. In this paper, we compare a constructed wetland (CW) based wastewater treatment plant to an activated sludge process (ASP) in Matamoros, Mexico. Greenhouse gas (GHG) emissions are calculated using life cycle assessment (LCA) and an economic viability assessment is carried out. Based on a literature review, both treatment methods are considered to produce sufficient treatment efficiency.

Water hyacinth was chosen as the aquatic plant in the CW due to its fast growth rate and the possibility of using it in anaerobic digestion (AD) to produce energy and fertiliser for agricultural land. In our calculations, the biogas produced from the water hyacinth biomass is the decisive factor when the two methods are compared. Direct GHG emissions from both methods are of the same order and are dominated by the GHG releases from the purification phase. However, if the water hyacinth can be used for energy production, the CW-based WWT not only fares better in economic terms, but also produces significant net climate benefits. Both methods studied have their downsides, increasing the need for risk evaluation. Although water hyacinth's fast growth rate is a crucial factor in the analysis, careful management is needed when cultivating the plant, as it has led to serious problems due to uncontrollable spreading. Furthermore, environmental and health risks must be identified and managed properly if wastewater-derived digestate is to be used on arable land, as assumed in the analysis. Additionally, N_2O leakages from the ASP and CH_4 and N_2O releases from the CW must be studied further to obtain reliable values for future analyses.

1. Introduction

Resource efficiency and reduction of environmental impacts is one key priority in all production and manufacturing processes. The issue is also discussed and developed in water treatment technologies, where water, energy, chemicals, and nutrients are increasingly considered resources to be conserved, reused and recycled. Water-energy nexus as an expression describes the interlinkage of the water and energy sectors (e.g. Scott et al., 2011; Siddiqi and Anadon 2011; Siddiqi et al., 2013). In recent years, the expression has been amended with nutrients to establish that within water technology, wastewater treatment (WWT) provides possibilities for nutrient recycling, and therefore water, nutrients and energy cycles should be seen as interrelated (e.g. Frijns et al., 2013).

Advanced WWT in developed countries is based on mechanical, biological, and chemical treatment, which is effective but requires resources for pumping, aeration, chemical production and transportation. With more stringent nitrogen (N) removal, infrastructure resources, operational energy, costs, direct greenhouse gas (GHG) emissions, and chemical consumption generally increase, which is challenging, particularly for small communities or developing countries. More demanding objectives, coupled with scarce resources of both financial and physical nature, create a need to develop innovative solutions both in technologies and operation models (e.g. Gunes et al., 2012). These solutions must fulfil the environmental requirements in a way that is also acceptable according to society's economic and social restrictions (UNEP, 2011 and OECD, 2011).

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http://dx.doi.org/10.1016/j.ecoleng.2017.04.017
0925-8574/

When reducing the use of chemicals and energy in WWT on environmental grounds, whilst at the same time demanding a reduction in organic material and nutrients, other technological methods have to be introduced. Decentralised technologies, such as land-based treatments, have been shown to have more potential in developing economies than conventional systems based on a set of sustainability indicators (Muga and Mihelcic 2008). Engineered wetland systems, constructed wetlands (CW), biological filters, and sand filtration systems have been proposed as feasible alternatives with lower environmental impacts, compared to conventional technologies, by a number of studies (Corominas et al., 2013). Although a decade ago CWs were still largely ignored as a WWT alternative in developing countries where effective, low cost WWT strategies were critically needed (Kivaisi 2001), an up-to-date look into the literature shows that CWs are now more widely applied than other technologies. Most of the studies evaluating the effectiveness of CWs as a WWT method, however, ignore the water-energy-nutrients nexus by classing outputs of the wastewater treatment plant (WWTP) as environmental burdens (e.g. Chunkao et al., 2012 and Gunes et al., 2012).

All resources in WWT processes could be used more effectively. In addition to decreasing energy and chemical consumption of WWT processes, the heat energy of the influent wastewater as well as the energy of the solids – mainly sludge that is separated from the water – could also be utilised. Besides energy, purified water itself has resource potential due to the lack and periodic fluctuation of water resources. Moreover, nutrients recoveredfrom the wastewatercan be used as soil amendments or fertiliser (Mo and Zhang 2013). Recovery of water, energy, and nutrients is a key consideration in discussion of what makes a particular WWT technology sustainable (Guest et al., 2009).

In this paper, the feasibility of a CW as a WWT method is evaluated from the resource efficiency point of view. Our case study focuses on a developing area: the state of Tamaulipas in North-East Mexico. The country is among the first developing countries to commit to reducing their GHG emissions. By 2020 and 2050, the reduction targets are 30% and 50%, respectively. Simultaneously, Mexico is aiming to produce 35% of its energy from renewable sources. According to USAID (2013) projections, improved WWT is among the ten measures with largest abatement potential in Mexico, equivalent to12 Mt CO_2eq by 2020, or 7% of the potential of the ten highest abatement methods.

We will calculate the energy balance of the CW-based WWT, assess the climate change impacts, and compare the results with a conventional treatment alternative: activated sludge treatment. In addition to this, we will evaluate the economic feasibility of the plant. Life cycle analysis (LCA) is used as method for evaluating the climate change impacts. The core research question in this study is whether developing economies should prioritise low technology WWT over more capital- and input-intensive processes for sustainably achieving a good level of sanitation. The cost of land required for CW is not considered in this paper because it is designed to be constructed on the same site using the same area as current WWTP. The additional land needed is not very large due to the efficiency of water hyacinth. The discussion on the land usage is in section Results and discussion.

2. Approach and methods

2.1. Life cycle assessment (LCA)

Life cycle thinking (LCT) is used to gain a holistic view of the environmental performance of the product, process or system being analysed. LCT expands the viewpoint beyond the more traditional view of process-specific environmental impacts by including all relevant upstream and downstream activities that potentially affect the life-long impacts. Within the field of WWT, LCA has been applied since the 1990s (see Corominas et al., 2013 for a review). In wastewater management, LCT can incorporate the key notion of avoided impacts, that is, activities that could potentially be avoided by utilising the resources in wastewater. In our analysis, such resources are energy from biomass and sludge, water for irrigation, and the nutrients in sludge.

Our analysis concentrates on the climate change impact of WWT, but we use a system expansion by allowing for the so-called substitution or avoided burden method (Guinée et al., 2002) by including the emissions avoided from activities that may potentially be replaced by the use of wastewater-derived outputs. Therefore, we distinguish between direct contributions from WWT, and indirect upstream contributions (e.g. provision of energy to the treatment processes), but also account for downstream contributions from processes that may potentially be replaced by end products from WWT. The start of the system boundary in the analysis is drawn at the raw sewage arriving at the WWTP and the end is at the point where the outputs have been transformed into a form where they can be utilised instead of virgin resources.

As energy consumption and possible energy gains from the system are of interest and serve as the basis from which the LCA proceeds; the energy balance of the system studied during its life cycle is also presented. A key issue in LCA with a system expansion is what kind of energy is replaced by the energy created in the system. This matter has been discussed rigorously in LCAs concentrating on waste management, since the replaced energy typically has the most significant impact on the outcome (e.g. Fruergaard et al., 2009). LCAs studying WWT in the same manner are still scarce, but the same discourse applies for wastewater, when energy is utilised and potentially replaces other energy sources. In the analysis, we use average data on Mexican electricity production (Swiss Centre for Life Cycle Inventories, 2014), but allow for variation in the sensitivity section, which shows how choices of different marginal energy forms affect the overall outcome. The life cycle chain includes emissions created during extraction and transportation of different fossil fuels. In the analysis we use the same energy sources for both upstream and downstream unit processes (e.g. Fruergaard et al., 2009). The upstream process energy data includes the effects of energy transition. LCI = suorat päästöt + epäsuorat päästöt – vältetyt päästöt

In evaluating the GHG impact we first employ a life-cycle inventory analysis (LCI) (Guinée et al., 2002; ISO 14040; ISO 14044). The derived GHG accounts are then reported as global warming potential (GWP) according to the rules of the Intergovernmental Panel on Climate Change (IPCC) (Solomon, 2007). We report the GWP as CO_2-equivalents per 1000 m^3 of influent wastewater. The emissions included are fossil carbon dioxide ($CO_{2,foss}$), biogenic carbon dioxide ($CO_{2,bio}$), methane (CH_4), and dinitrogen oxide (N_2O). Their characterisation factors used for converting each emission into its GWP are 1, 0, 25, and 298, respectively (Solomon, 2007). The calculations are carried out simply by using an equation that gives the emission by adding direct and indirect emissions and then subtracting the avoided emissions of the process in question.

We use 1000 m^3 of influent wastewater as the functional unit of the study. All inputs, outputs, emissions and results are quantified relative to 1000 m^3 of influent wastewater.

2.2. Economic viability analysis

The analysis of economic viability is performed by comparing the investment and operational costs of the planned CW (including sludge and WH biomass digesting) with a conventional activated sludge process (ASP) (including sludge digesting). Estimated costs of the CW are based on values provided by a consultant designing