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A comparative assessment of anaerobic digestion power plants as alternative to lagoons for vinasse treatment: life cycle assessment and exergy analysis

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A B S T R A C T

The treatment of vinasse in lagoons causes methane emissions during the anaerobic decomposition of the organic matter. The recovery of this methane, to produce renewable energy in anaerobic digestion power plants (ADPPs) replacing fossil fuels and reducing greenhouse gas emission, could bring environmental benefits. The aims of this work were: (1) to compare alternatives of ADPPs available for the treatment of vinasse; and (2) to evaluate the impacts of ADPPs as alternative for lagooning Cuban vinasse; both by means of Life Cycle Assessment (LCA) and exergy analysis (EA). The LCA and EA showed that the ADPPs improve the environmental profile with respect to the lagooning of vinasse, reducing up to 77% the total score and recovering up to 46% of the exergy extracted from the natural environment during the process, respectively. The highest environmental benefits for the ADPPs were observed when the subprocesses biogas production from raw vinasse, sulfide removal by biooxidation with air oxygen addition and energy generation in spark ignition engines were used. In that case, the treatment of 1072 ton of vinasse (exergy content of 740.6 GJ_{ex}) can produce 175 GJ_{ex} as “electricity and heat”, 191 GJ_{ex} as “wastewater for fertirrigation”, 21.7 GJ_{ex} as “digestate”, and 0.41 GJ_{ex} as “sulfur in the filter cake”. This way, the produced 1.3 million cubic meters of vinasse ($1.34 \cdot 10^6$ ton/year) reported by the Cuban Ministry of the Cane Sugar Industry can replace 485263 GJ_{ex} per year as energy and bio-fertilizers, reducing the negative environmental impacts for the studied categories.

1. Introduction

Vinasse is the liquid wastewater obtained after distillation of sugar-cane molasses in ethanol factories. Most distillery wastewaters are highly polluted and considered to be medium–high strength wastewaters (Ince et al., 2005). In Cuba, most of the cane-molasses vinasses (≈99%) are treated in lagoons where methane, carbon dioxide and hydrogen sulfide emissions have been reported as a result of uncontrolled anaerobic decomposition of the organic matter (Safley and Westerman, 1988; Toprak, 1995). As methane is an important greenhouse gas that has a global warming potential of 34 CO_2-equivalents over a 100 year time horizon (IPCC, 2013), the principal environmental damage reported for lagooning is the methane emission (Chen et al., 2013). Typically, the liquid effluent

Abbreviations: ADPP, Anaerobic digestion power plant; BP, Biogas production; COD, Chemical oxygen demand; CHP, Combined heat and power; EA, Exergy analysis; EG, Energy generation; EDTA, Ethylenediaminetetraacetic acid; FP, Fertirrigation pumping; IDA, Iminodiacetic acid; LS, Lagooning; LCA, Life Cycle Assessment; LHV, Lower heating value; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; L, Organic ligand; n, Charge of the organic ligand; OLR, Organic loading rate; SD, Sludge drying; SWW, Sugar wastewater; SR, Sulfide removal; TSC, Traditional supply chain; UASB, Upflow anaerobic sludge bed.

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Nomenclature

COD_s	COD content of the stream, kg COD
$COD_{removed}$	Removed COD, kg COD d^{-1}
c_p	Heat capacity of the substance, kJ kg^{-1} K^{-1}
Ex_{ch}	Chemical exergy, GJ_{ex}
Ex_e	Electrical exergy, GJ_{ex}
Ex_S	Solar exergy, GJ_{ex}
Ex_{ph}	Physical exergy, GJ_{ex}
Ex_{tot}	Total exergy of a product or process, GJ_{ex}
eff_COD	Effluent COD concentration, g COD$\cdot$ m^{-3}
θ_h	Mean hydraulic retention time, D
inf_COD	Influent COD concentration, g COD$\cdot m^{-3}$
k_{20}	COD removal rate coefficient at 20 °C, d^{-1}
k_T	First-order COD removal rate coefficient, d^{-1}
m	Mass of the substance, Kg
T_{lag}	Lagoon liquid temperature, °C
T_{air}	Averaged ambient air temperature, °C
T	Temperature of the substance, K
T_0	Reference temperature, K
τ	temperature correction factor, –
R_{CH4}	Methane production rate, L$\cdot m^{-2}$ d^{-1}
η_{ex}	Exergy efficiencies, %

of the lagoons has been used for fertirrigation of the sugar cane plantations while the sludge recovery for fertilization has been less frequent due to the absence of a proper recovery system in the lagoons.

However, vinasse is very suitable for anaerobic digestion, producing biogas ($\approx$60% methane) being a versatile gas fuel that can replace fossil fuels in power and heat generation plants. The energetic value of biogas and its potential to save fossil carbon emissions (Budzianowski, 2011) together with the additional digestate production and COD removal are the principal benefits of anaerobic digestion (Contreras et al., 2009; Nandy et al., 2002). The only biogas production process in Cuba treating vinasse (800 m^3 of vinasse per day) has been designed to treat diluted vinasse (20 kg COD m^{-3}). In this process, vinasse is diluted by using sugar wastewater (SWW) during the sugar factory working days (100 days). As distilleries are operated 300 days, vinasse is diluted by using tap water during the remaining 200 days. Moreover, this biogas production process in Cuba requires the addition of chemicals for neutralization, while the thermal energy contained in vinasse is released into the environment. In contrast, "raw vinasse" (COD $\geq$ 38 kg COD m^{-3}) can be neutralized and diluted with the liquid effluent of the biogas production process only (Barrera et al., 2014; Nandy et al., 2002), saving the use of chemicals for neutralization and tap water for dilution and recovering the thermal energy contained in vinasse. Because of the addition of sulfuric acid and ammonium sulfate at the ethanol factory, vinasse is a sulfate-rich liquid substrate for anaerobic digestion (Barrera et al., 2013). Thus, the anaerobic digestion of vinasse leads to high H_2S concentrations in biogas ranging from 14 000 to 55 000 ppm_v (Barrera et al., 2014). The removal of H_2S is a prerequisite for the utilization of biogas to avoid corrosion of the energy conversion systems. Elemental sulfur that can be used as fertilizer may be produced during the sulfide removal process and separated by means of filters producing a filter cake. Absorption into ferric chelate solution, absorption into aqueous ferric sulfate solution and biooxidation with air oxygen addition have been suggested to remove H_2S from biogas obtained during the anaerobic digestion of vinasse (Barrera et al., 2013). These sulfide removal technologies differ from each other in the amount of chemicals and energy (electricity and heat) demanded for operation as well as in the amount of sulfur produced in the filter cake.

Additionally, combined heat and power engines (CHP) are typically used to convert biogas into energy (electricity and heat). The H_2S limitations in the fueled biogas vary from one to another CHP application, i.e. spark ignition engines and gas turbines allow H_2S levels between 100 and 250 ppm_v, while boiler-steam turbines allow levels up to 1000 ppm_v (Weiland, 2010; Wellinger and Linberg, 2000). These differences cause variations in the energy required and the sulfur produced (in the filter cake) during the sulfide removal process as well as in the SO_x emissions during the combustion of hydrogen sulfide in the CHP engine. Therefore, variations in the mass and energy flows of biogas production, sulfide removal and energy generation subprocesses produce variations in the mass and energy flows of the whole anaerobic digestion power plant (ADPP). The combination of these subprocesses creates several alternatives of ADPPs for the treatment of vinasse, whereas the inclusion of an ADPP as a first treatment step creates a new scenario with respect to the lagooning of Cuban vinasse. By determining the environmental sustainability of these scenarios useful information can be provided to support decision makers.

In order to quantify the environmental sustainability of alternative products, processes or services, the methodology of Life Cycle Assessment (LCA) is commonly used (Casas et al., 2011; Contreras et al., 2009; De Meester et al., 2012; Gil et al., 2013). LCA is a powerful tool to identify the different environmental aspects and the potential environmental impact of a product or service throughout its life cycle from raw materials to production, use, collection and end-of-life treatment including any recycling and disposal (European-Commission, 2010).

The exergy concept can be also applied because exergy quantifies the ability to cause change and it is not fully conserved, in contrast to energy, which allows it to expose the inefficiency of processes (Dewulf et al., 2008). During the exergy analysis, exergy consumption as well as exergy efficiency of the different subprocesses (process level) and of the entire production system (gate-to-gate) can be determined.

Some works have been addressed to assess the environmental sustainability of the biogas production process in different scenarios (Afrane and Ntiamoah, 2011; Aye and Widjaya, 2006; Contreras et al., 2009; Rocha et al., 2010) in a life cycle perspective, considering the process as a whole (black box) and leaving out the study of the type of technology that can be used at each subprocess in the ADPPs (e.g. biogas production from diluted or from raw vinasse and energy generation in spark ignition engines or in boiler-steam turbines). Although the environmental sustainability of ADPPs as a biomass valorization technology has been assessed based on exergy analysis as well (De Meester et al., 2012), little research has been done to compare alternatives of ADPPs available for the treatment of vinasse and to assess the impact of ADPPs on the lagooning of Cuban vinasse.

Therefore, the aims of this work were: (1) to compare alternatives of ADPPs available for the treatment of vinasse; and (2) to evaluate the impacts of ADPPs as alternative for lagooning Cuban vinasse; by making a comparative study from a life cycle perspective (LCA) and by determining the process inefficiencies by means of exergy analysis (EA).

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