Use of life cycle assessment to evaluate environmental impacts associated with the management of sludge and biogas

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ABSTRACT

Upflow anaerobic sludge blanket (UASB) reactors used in sewage treatment generate two by-products that can be reused: sludge and biogas. At the present time in Brazil, most of this resulting sludge is disposed of in sanitary landfills, while biogas is commonly burned off in low-efficiency flares. The aim of the present study was to use life cycle assessment to evaluate the environmental impacts from four different treatment and final destination scenarios for the main by-products of wastewater treatment plants. The baseline scenario, in which the sludge was sanitized using prolonged alkaline stabilization and, subsequently, directed toward agricultural applications and the biogas destroyed in open burners, had the most impact in the categories of global warming, terrestrial ecotoxicity, and human non-carcinogenic toxicity. The scenario in which heat resulting from biogas combustion is used to dry the sludge showed significant improvements over the baseline scenario in all the evaluated impact categories. The recovery of heat from biogas combustion decreased significantly the environmental impact associated with global warming. The combustion of dried sludge is another alternative to improve the sludge management. Despite the reduction of sludge volume to ash, there are environmental impacts inherent to ozone formation and terrestrial acidification.

Key words | environmental impacts, life cycle assessment, UASB reactor, wastewater treatment

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INTRODUCTION

Upflow anaerobic sludge blanket (UASB) reactors became popular with Brazilian researchers and design engineers in the 1980s, largely because of the strong influence of authors such as Lettinga and van Der Meer (Aisse 2000). These reactors essentially consist of a vertical flow tank with overlapping sedimentation and anaerobic digestion chambers (Aisse 2000; Chernicharo *et al.* 2015). These reactors must effectively separate both sewage biogas and sludge, which are by-products of this technology (Lettinga *et al.* 1980; Chernicharo *et al.* 2015). By numbers, UASB reactors are the third most common technology used in wastewater treatment plants (WWTPs) in Latin America and the Caribbean (17%) and rank number two in Brazil (30%) (Noyola *et al.* 2012). UASB reactors (along with stabilization ponds) generate less sludge than other treatment systems.

Today, treatment and final disposal of sewage sludge is one of the most complex problems faced in the sanitation engineering area and by municipal managers (Garrido-Baserba *et al.* 2015).

In Brazil, landfills are the most common final destination for sludge; this leads to high transport costs and waste of the nutrient and/or energetic potential of the dehydrated sludge. In order to control the environmental liabilities associated with discarding sludge in sanitary landfills, some countries have advanced by imposing restrictive measures regulating the physical conditions of the material to be disposed (Cieślik *et al.* 2015).

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Agricultural application carries out the recycling of the nutrients that are present in the sludge. In countries like China, France, New Zealand, and the USA, these biosolids are sold to farmers and are consequently valued as a marketable product (Bittencourt *et al.* 2014). In Brazil, disposal of sewage sludge in agriculture is regulated by Resolution 375 of the National Environmental Council (Brasil 2006). The control measures in this legislation include establishment of maximum concentration limits for inorganic contaminants (metals), pathogens, and bacteriological indicators (Bittencourt *et al.* 2014).

Prolonged alkaline stabilization (PAS) is a sludge treatment process that can be used to reach the parameters established in environmental resolutions. The process is used to treat primary, secondary, or digested sludge, and involves adding enough lime to the sludge in order to increase the pH up to 12, reducing the population of microorganisms and the odor potential. Quicklime (calcium oxide, CaO) and hydrated lime ($Ca(OH)_2$) are most commonly utilized. Studies have shown that CaO dosages equivalent to 30%–50% of the dry weight of the sludge can attain the characteristics required to produce biosolids. After mixing, the sludge should remain in a covered area for 60 to 90 days to complete the sanitization (Andreoli *et al.* 2014).

Thermal treatment is an alternative to treat and to sanitize the sludge. The potential for energy generation at WWTPs is a function of several factors that positively influence the energy potential of the biogas: greater sewage concentrations, increased efficiency in removing chemical oxygen demand (COD), and lower rates of methane loss. The heat from biogas combustion in WWTPs can be used within the plants themselves to dry the sludge. Besides, the dry sludge combustion produces both ash and heat, which can be used to dry the sludge. In Brazil, few WWTPs utilize the biogas to recover heat, and in most cases this resource is only destroyed in low-efficiency burners (Rosa *et al.* 2016).

The dry sludge combustion process has the advantage of reducing the final volume of solid materials to be disposed of. As for the ash generated, the process almost completely degrades organic pollutants and transfers carbon and nitrogen into their gaseous forms. However, other components such as phosphorus, silicon, and most metals are concentrated in the ash (Cieślik *et al.* 2015; Kruger & Adam 2015). In the sludge management process, an additional step to immobilize heavy metals may be necessary (Liu & Qu 2016). Further treatment of the ash is required to reduce the amount of heavy metals and increase the bioavailability of phosphorus for agricultural use (Cieślik *et al.* 2015).

In order to contribute to the development of public policies, a number of researchers have conducted life cycle assessment (LCA) for sewage sludge (Wang *et al.* 2013; Yoshida *et al.* 2013; Mills *et al.* 2014; Xu *et al.* 2014; Garrido-Baserba *et al.* 2015). LCA focuses on potential environmental aspects and impacts (use of resources and consequences for the environment) throughout the product life cycle (ABNT 2009). Similarly, life cycle impact assessment provides additional information to aid in the performance of a life cycle inventory (LCI) for a product system in order to obtain better understanding of its environmental significance (ABNT 2009). However, it is incipient in the literature that the LCA approach is being applied to manage sludge and biogas from UASB reactors.

In this context, the aim of the present study was to use the LCA as a tool to evaluate the environmental impacts resulting from different treatment and final destination scenarios for the sludge and biogas from UASB reactors treating domestic wastewater through integrated management. The medium-sized WWTP analyzed in this study is located in southern Brazil. In a sense, the paper introduces some new perspectives for environmental sustainability associated with by-product integrated management from UASB reactors based on full scale data and accurate LCI.

METHODS

Area of study

The data used in the inventory for the baseline scenario were obtained in 2014 and 2015 from a WWTP located in southern Brazil.

This plant has the capacity to treat 440 L/s of domestic sewage and serves a maximum population of 235,000 inhabitants. For preliminary treatment, the plant uses two mechanized screens and one grit chamber; for the biological treatment stage, the plant has six UASB reactors (secondary treatment) and two aerated facultative ponds (post-treatment). The sludge produced in the UASB reactors and the aerated ponds is periodically discarded after gravity thickening and subsequent dewatering in a centrifuge. Next, the sludge undergoes PAS, and then is directed toward agricultural uses. The biogas generated by the UASB reactors at the plant is destroyed in open flares.

Outline of the studied scenarios

This study compares four different scenarios for treatment and final destination. The functional study unit is the management of the by-products (sludge and biogas) generated from treating 1,000 m^3 of sewage, encompassing the phases of treatment and final disposal. The reference flows are 52.16 Nm^3 of biogas (69.43% CH_4) and 2,508 kg of sludge (20% total solids) obtained from the UASB reactors. Figure 1 illustrates the system boundary and highlights the case study and proposed scenarios. The baseline scenario corresponds to the process at the WWTP described in this study. The stabilized sludge is dewatered in a centrifuge and then undergoes PAS using quicklime. The sanitized sludge is directed to agriculture and the biogas generated by the reactors is destroyed in low-efficiency flares. In Scenario 1, the biogas generated is used as a heat source to dry the sludge in a rotary dryer, and the dried and sanitized sludge is directed toward agriculture. In Scenario 2, the sludge is combusted, and the heat generated is used to dry the dewatered sludge; because the sludge's calorific value is insufficient to dry the sludge, a percentage of the biogas generated is also used. Ashes from this process are directed toward agriculture. Scenario 3 is similar to Scenario 2, but the ashes are discarded in a landfill.

Developing the environmental inventories

The guidelines from ISO standards series 14,040 were adopted to conduct the LCI for the treatment and final disposal of the sludge and biogas.

The biogas generated by the UASB reactors is burned in open flares, with an efficiency of approximately 50%. The calculated methane content of the biogas was 69.43%, considering COD loads, treatment efficiency, and the sewage flow from the WWTP. The software PROBIO 1.0 (Possetti *et al.* 2015a) was used to calculate these estimates, and the model by Lobato *et al.* (2012) was also used.

Baseline scenario

The baseline scenario describes the treatment and final destination adopted in the WWTP operation analyzed. The data for sludge volume, total solids content, polymer consumption, lime consumption, volume of dewatered sludge, and electricity consumption of the equipment were surveyed in 2014 and 2015. Sludge density (1,030 kg/m^3 and 1,050 kg/m^3), as described by Andreoli *et al.* (2014), was used to determine the sludge mass, expressed in kg.

Emissions related to transporting the products consumed in the sludge treatment process (using the distances from the chemical manufacturers to the WWTP) and directing the treated sludge to the agricultural area were reported as tkm units, which consider the amount transported and the round-trip distance traveled.

The fuel consumption rates for the wheel loader used for liming the sludge and the spreader used to apply the dried sludge to the fields are 13 L/h and 10 L/h, respectively,

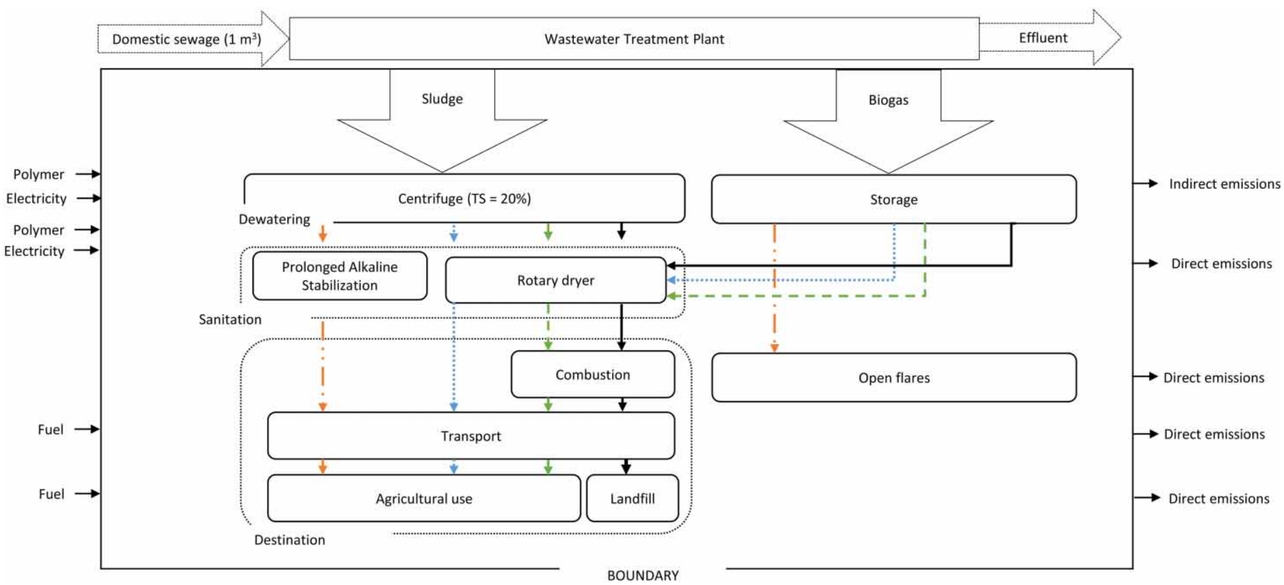

Figure 1 | Scenarios for treatment and final disposal of sludge and biogas from WWTP. Legend: baseline scenario (→): sludge is dewatered in the centrifuge, undergoes PAS, and is destined for agricultural use, while biogas is destroyed in an open flare. Scenario 1 (→): Biogas is used as a heat source to dry the sludge in a rotary dryer, and the dried sludge is used in agriculture. Scenario 2 (→): Sludge is combusted and the heat generated is used to dry the dewatered sludge, while ashes are directed toward agriculture. Scenario 3 (→): Identical to Scenario 2, but ashes are discarded in the landfill.

and this equipment has an application capacity of 85 t/day and 200 t/day. The calorific value of the diesel used is 3.85 kWh/L. Direct atmospheric emissions from the equipment used for sludge liming and spreading the sludge were calculated according to emission factors for diesel engines: CO (0.830 g/kWh), NOx (1.800 g/kWh), and particulate matter (0.018 g/kWh) (Brasil 2011).

The emissions from applying quicklime for sanitization (losses of N and C expressed in NH_3 and CO_2) were calculated using the sludge content before lime application, with values of 2.81% for N (Aisse 2000; Andreoli *et al.* 2014) and 15% for C (Ross *et al.* 2014).

Emissions related to agricultural application in agriculture followed the models presented by Nemecek & Schnetzer (2011), which are shown in Table 1.

The input data for the model (N and P content in the sludge and soil) comprised the mean values for the last 3 years for the regions that received the sludge: 10.2 g/kg for N and 3.6 g/kg for P. In applying the sludge to the soil, it was take into account as the avoided products: urea (45% nitrogen), phosphate fertilizer (P_2O_5), and agricultural lime (relative neutralizing value = 75%).

Scenario 1

The environmental inventory for Scenario 1 was prepared using data collected from a pilot rotary dryer installed in a similar WWTP in the same area; the operational data for the installed system are shown in Table 2. The methodologies for conducting the inventory related to the centrifugation and agricultural application stages were the same as those presented in the baseline scenario.

In order to calculate the volume of biogas required to dry the sludge, values were used from the previous two years for the chemical energy required to evaporate the water mass of the sludge generated; in the pilot experiment, 1,323.9 kcal were needed to evaporate 1 kg of water contained in the sludge. The biogas burn efficiency of the dryer used was 85%. The effluent return from the gas scrubber was directed to the WWTP itself, and consequently the environmental inventory for the station was conducted (Amaral *et al.* 2016). The atmospheric emissions from the dryer were collected from measurements performed onsite in the pilot experiment. The analyses were conducted in an independent laboratory and comprised assessments of particulate matter (gravimetric analysis), organic gaseous substances (gas chromatography coupled to a mass spectrometer), carbon monoxide, and nitrogen oxides (detection by electrochemical cells).

The agronomic data (nitrogen and phosphorus) to calculate the products avoided (urea and superphosphate fertilizer) and levels of heavy metals in the dry sludge were obtained by analyzing batches collected three times a day during the course of one year. The values found for N and P in the sanitized sludge were 5.93 and 0.97 g/kg, respectively. Emissions related to the agricultural application of sludge were calculated using the models presented by Nemecek & Schnetzer (2011). The application rate followed the recommendations of Paraná Agency (Paraná 2009). These rates are established according to the available nitrogen concentration in sludge, using a rate of 90,311 kg TS/ha.

Table 1 | Models used to calculate emissions related to the application of sludge in agriculture

Emission	Parameter	Model used
Air	NH_3	Agrammon
	N_2O	IPCC method
	NO_X	IPCC method
Groundwater	NO_3	SQCB
	PO_4	SALCA – P
	Heavy metals	SALCA – Heavy metals
Surface water	PO_4	SALCA – P
Soil	Heavy metals	SALCA – Heavy metals

Table 2 | Operational data for pilot sludge drying system

Item	Data
Operational sludge feed	(94.8 ± 33.8) kg/h
Total solids of sludge entering the system	(23.5 ± 1.4) %
Total solids of sludge exiting the system	(84.0 ± 1.3) %
Reduction in sludge mass	79%
Flow rate for biogas rate used in the system	(15.1 ± 7.5) Nm^3/h

Source: Possetti *et al.* (2015b).

Scenario 2

In this scenario, the sludge is combusted and the ash is used in agriculture. The lower calorific value of dry sludge, according to Possetti *et al.* (2015b), is 2,497.84 kcal/kg. Atmospheric emissions from the dryer were obtained from onsite measurements. The agronomic data used in calculating the products avoided (urea and superphosphate fertilizer) and the heavy metals contained in the ash were taken from ash analysis obtained by combusting dry anaerobic sludge under laboratory conditions in a muffle furnace at 1,000 °C. The values for N and P found in the ash were

34.72 and 20.57 g/kg, respectively. According to Liu & Qu (2016), available phosphorus accounts for 31% of the total value. The methodologies used to conduct the inventory for the centrifugation and agricultural application stages were identical to those used in the baseline scenario.

Scenario 3

Scenario 3 resembles Scenario 2, but the ash generated is discarded in a landfill. The real value for the distance traveled from the WWTP to the landfill was used: 27 km (round trip). The same methodology for Scenario 2 was used to conduct the environmental inventory, using the sanitary landfill from the Ecoinvent v3 database (Municipal solid waste {RoW} | treatment of, sanitary landfill | Alloc Def, U).

Assessment of environmental impacts

The LCA methodology and stages were used to calculate the environmental impact, along with SimaPro software, version 8.4. To evaluate environmental impacts, the ReCiPe 2016 Midpoint (H) method was used. The impact categories evaluated were: global warming (GWP), stratospheric ozone depletion (ODP), ozone formation, terrestrial ecosystems (OF_TE), terrestrial acidification (TAP), freshwater eutrophication (FEP), terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP) and human non-carcinogenic toxicity (HTPnc). These categories were selected because they consider important element flows through the assessment method and because they were featured in a number of studies on LCA in WWTPs (Tarantini *et al.* 2007; Wang *et al.* 2013; Xu *et al.* 2014).

The uncertainty analysis was performed using the pedigree matrix through a Monte Carlo simulation in the software. To use this simulation, the Standard Deviation (SD) of each inventory life cycle input was obtained by the combination of Pedigree Matrix, Basic Uncertainty Matrix and Pedigree Vector. The Pedigree Vector, resulting from the classification made in this study, as well as the Basic Uncertainty and the SD of each input are in the supplementary material (available with the online version of this paper).

RESULTS AND DISCUSSION

Environmental inventories

Table 3 shows the environmental inventories for each scenario investigated. All values speak about 1,000 m^3 effluent treatment. That embraces the treatment and final destination of sludge and biogas. Sanitization using PAS (baseline scenario) generates the largest amount of sanitized sludge to be used but produces the lowest emissions of CO (3.59×10^{-03} kg) and NO_x (7.78×10^{-03} kg). The rotating dryer using biogas heat (Scenario 1) has the highest CO emissions (1.77 kg), while the rotary dryer using heat from sludge combustion (Scenario 2 and 3) has the highest NO_x emissions (0.28 kg).

In final disposal, agricultural application of sludge sanitized using PAS (baseline scenario) has the highest values for avoided products, namely urea (1.48 kg), superphosphate fertilizer (0.54 kg), and agricultural lime (43.60 kg), but is also responsible for the highest emissions of heavy metals into the water and soil. The scenario using the heat produced from sludge combustion (Scenario 2) produces the highest atmospheric emissions of NH_3 (0.58 kg) and N_2O (0.02 kg).

Assessment of environmental impacts

Figure 2 shows percentages of each scenario in terms of comparison with the baseline scenario. The absolute values for each scenario by step are presented in the supplementary material (available with the online version of this paper). Error bars are the uncertainty analysis conducted for 1,000 iterations, with a 95% confidence interval.

For the global warming category, all scenarios demonstrated improvements over the baseline scenario (497 kg CO_2eq), using PAS for sludge sanitization. The steps in this category with the greatest impacts were the burning of biogas in open flares, through CH_4 emissions (89%), and sanitization using PAS (7.7%). For this category, Scenario 2 (143 kg CO_2eq) had the least impact, using heat from sludge combustion for drying and sanitizing, and had 71% less impact for this category in comparison with the baseline scenario. Methane emissions from burning biogas made the largest contribution to this category, representing more than 78% in all scenarios evaluated. The efficiency of the thermal dryer could be improved, because the market has other options, such as belt dryers. However, in this case study there was excess heat from biogas and dried sludge. In a sense, the results from LCA are similar. Besides, the rotary dryer is a solution adopted to regional conditions, which was evaluated in pilot scale. The environmental impact of the baseline scenario could be reduced by using a high-efficiency burner (98%), which is already available in the market. By using this equipment,

Table 3 | Inventory of treatment and final disposal of sludge and biogas referring to the treatment of 1,000 m^3 effluent

Process		Amount (by Scenario)			
		Baseline	**S1**	**S2**	**S3**
Dewatering	**Input**				
	Sludge (kg)	2,508	2,508	2,508	2,508
	Polymer (0.3%) (kg)	0.19	0.19	0.19	0.19
	Transport (tkm)	0.18	0.18	0.18	0.18
	Electricity (kWh)	6.05	6.05	6.05	6.05
Sanitization	Dewatered sludge (kg)	306	306	306	306
	Lime (kg)	33.08	–	–	–
	Energy (biogas) (kWh)	–	336	99.26	99.26
	Thermal energy (Sludge) (kWh)	–	–	221.25	221.25
	Electricity (kWh)	–	38.28	38.28	38.28
	Transport (lime) tkm	3.37	–	–	–
	Fuel (L)	1.12	–	–	–
	Output				
	Water (kg)	133.70	229.85	233.49	233.49
	NH_3 (kg)	1.16	–	–	–
	CO_2 (kg)	1.88	–	–	–
	CO (kg)	3.59×10^{-03}	1.77	0.40	0.40
	NO_x (kg)	7.78×10^{-03}	0.03	0.28	0.28
	SO_x (kg)	–	0.03	3.35	3.35
	∑BTEX (kg)	–		6.15×10^{-03}	6.15×10^{-03}
	Dioxins (kg)	–		2.34×10^{-06}	2.34×10^{-06}
	Particulates (kg)	7.78×10^{-05}	0.18	0.49	0.49
	Effluent (L)	–	107.63	102.51	102.51
Destination	**Avoided products**				
	Urea (kg)	1.48	0.89	2.30	–
	P_2O_5 (kg)	0.54	0.15	0.19	–
	Agricultural lime (kg)	43.60	–	–	–
	Input				
	Sanitized sludge/ash (kg)	205.38	76.36	29.78	29.78
	Transport (tkm)	38.45	14.29	5.57	0.80
	Fuel (L)	0.08	0.03	0.01	–
	Output				
Air	NH_3 (kg)	0.34	0.21	0.58	–
	N_2O (kg)	0.01	9.14×10^{-3}	0.02	–
	NO_X (kg)	3.78×10^{-3}	2.13×10^{-3}	4.71×10^{-3}	–
	CO (kg)	2.63×10^{-04}	9.76×10^{-05}	3.81×10^{-05}	–
	Particulates (kg)	5.69×10^{-06}	2.12×10^{-3}	8.26×10^{-04}	–
Groundwater	NO_3 (kg)	0.05	0.02	0.07	–
	PO_4 (kg)	3.56×10^{-04}	6.76×10^{-05}	4.91×10^{-04}	–
Surface water	PO_4 (kg)	2.34×10^{-3}	5.18×10^{-04}	1.75×10^{-13}	–
Water	Cd (kg)	1.82×10^{-7}	0	0	–
	Cu (kg)	1.64×10^{-05}	2.70×10^{-06}	1.16×10^{-05}	–
	Zn (kg)	1.46×10^{-04}	2.43×10^{-05}	7.67×10^{-06}	–
	Pb (kg)	2.36×10^{-06}	4.32×10^{-07}	0	–
	Ni (kg)	0	0	0	–
	Cr (kg)	9.47×10^{-05}	0	1.68×10^{-05}	–
	Hg (kg)	5.93×10^{-09}	0	0	–

(*continued*)

Table 3 | continued

Process		Amount (by Scenario) Baseline	S1	S2	S3
Soil	Cd (kg)	1.60×10^{-06}	0	0	–
	Cu (kg)	1.45×10^{-3}	4.49×10^{-06}	1.92×10^{-05}	–
	Zn (kg)	0.011	1.09×10^{-05}	3.43×10^{-06}	–
	Pb (kg)	4.85×10^{-04}	4.17×10^{-06}	0	–
	Ni (kg)	3.54×10^{-04}	5.11×10^{-06}	7.67×10^{-06}	–
	Cr (kg)	4.85×10^{-04}	0	5.68×10^{-06}	–
	Hg (kg)	4.19×10^{-05}	0	0	–
Biogas	**Input**				
	Biogas (Nm^3)	52.16	52.16	52.16	52.16
	Output				
	CO_2 (kg)	45.91	70.84	70.84	70.84
	H_2 (kg)	0.14	0.14	0.14	0.14
	SO_2 (kg)	0.23	0.19	0.19	0.19
	CH_4 (kg)	12.97	3.89	3.89	3.89
	N_2 (kg)	10.45	10.45	10.45	10.45
	Heat (MJ)	648.67	1,103	1,103	1,103

the impact in this category reduces by 85%, obtaining a value of 73.7 kg of CO_2eq.

In the ozone formation (terrestrial ecosystems) category, Scenarios 2 (0.2886 kg NO_xeq) and 3 (0.2960 kg NO_xeq) have a high potential for impact in comparison with the baseline scenario (0.1393 kg NO_xeq), 107% and 112%, respectively. These scenarios were higher due to increasing NO_x emissions during sludge combustion; in Scenario 2 this stage was responsible for 99%, and 97% in Scenario 3.

Scenario 1 (0.6772 kg SO_2eq) showed a 79% decrease in potential environmental impact for the terrestrial acidification category, in comparison with the baseline scenario (3.2551 kg SO_2eq). Sludge sanitization made the largest contribution to this category. In the baseline scenario, this step accounted for 72% of total impact; NH_3 emissions during the process of sludge liming had the greatest impact on this category, representing 70% of the total impact. In Scenarios 2 and 3, the combustion of sludge accounted for 78% and 95% of the total impact value, respectively. The

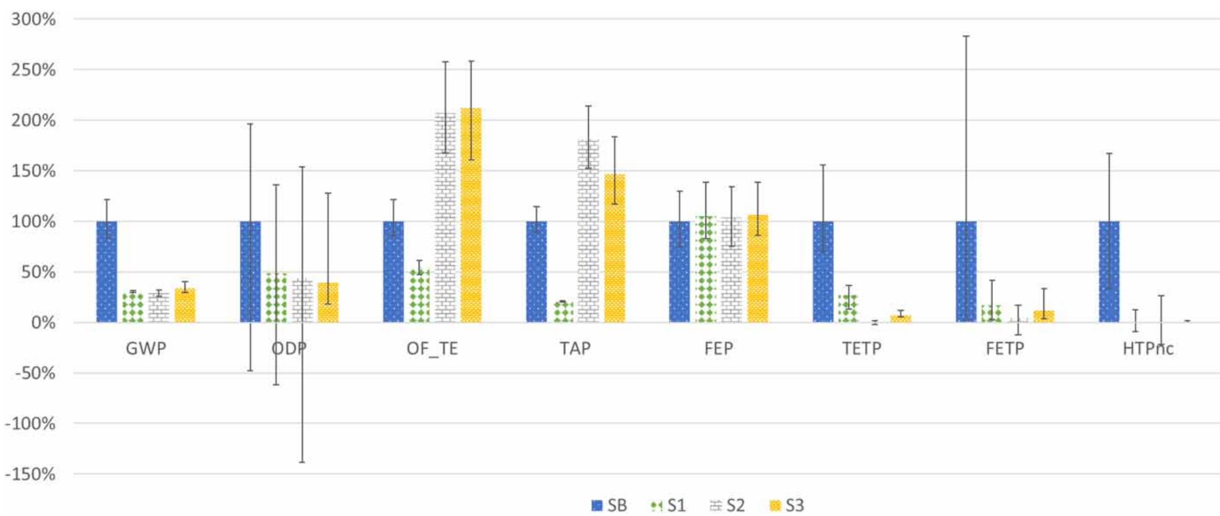

Figure 2 | Percentage comparative analysis between baseline scenario and other scenarios of treatment and final disposition of biogas and sludge. Legend: GWP, global warning; ODP, Stratospheric ozone depletion; OF_TE, ozone formation (terrestrial ecosystems); TAP, terrestrial acidification; FEP, freshwater eutrophication; TETP, terrestrial ecotoxicity; FETP, freshwater ecotoxicity; HTPnc, human non-carcinogenic toxicity.

contributing elemental flows were nitrogen and sulfur oxide emissions from combustion, with SO_x emissions accounting for 57% of environmental impact for this category in Scenario 2 and 70% in Scenario 3.

For terrestrial toxicity, all the scenarios showed improvement over the baseline scenario (0.0530 kg of 1,4 DBeq). The step that contributed the most to this category in the baseline scenario was transporting the sludge to its final destination, because of the copper emissions resulting from brake wear (75%). In the baseline scenario, this was the largest contribution, because of the greater volume of sludge requiring transport to final disposal.

All the scenarios demonstrated improvement over the baseline scenario (14,348 kg of 1,4DBeq) for human non-carcinogenic toxicity, a reduction of 99%. In the baseline scenario, agricultural use made the most significant contribution (99%), with zinc emissions into the soil accounting for 98%.

There are no significant statistical differences between the scenarios for the categories stratospheric ozone depletion (ODP), FEP and freshwater ecotoxicity (FETP), although the baseline scenario contributes to N_2O emissions in agriculture.

In general, the baseline scenario, in which the sludge is directed toward agricultural use and the biogas is burned in open flares, had the greatest impact in the categories of global warming, terrestrial ecotoxicity, and human non-carcinogenic toxicity.

Scenario 1, which utilized integrated management of sludge and biogas, did not have the largest environmental impact in any of the categories evaluated. The use of biogas in this scenario reduced environmental impacts for global warming (69%), ozone formation (45%), terrestrial acidification (79%), terrestrial ecotoxicity (72%), and human non-carcinogenic toxicity (83%).

It should be stressed that LCA is not a tool which is capable of assessing which process is more efficient, since it does not measure the real environmental impacts of the process, but instead calculates potential impacts. The results may also vary according to evaluation methods or base data used.

CONCLUSIONS

The results obtained shown that the recovery of heat from biogas combustion to dry sludge significantly decrease the environmental impact associated with global warming, especially because the open flare has low efficiency to destroy methane.

About the treatment and final disposal of sludge, it was observed that sanitization by means of quicklime (baseline scenario) increases the final volume of the sludge, increasing the environmental impact associated with terrestrial ecotoxicity. Besides, the combustion of the dried sludge increase the environmental impact inherent to ozone formation and terrestrial acidification due to the conversion of nitrogen and sulfur present in sludge in NO_x and SO_x emissions.

Finally, the LCA showed that the use of biogas generated in UASB reactors to dry sludge has the potential to reduce environmental impacts for all evaluated categories. Sludge combustion and using heat to dry sludge (Scenarios 2 and 3) have a higher potential impact in the categories of terrestrial acidification and ozone formation (terrestrial ecosystems). Scenario 1 showed an improvement over the baseline scenario for all evaluated categories in which significant differences were obtained. The use of biogas in WWTPs to dry sludge is a viable option and the biogas generated in the plant was sufficient to dry the sludge, with reduced environmental impacts in all areas evaluated. It is important to highlight that the obtained data were extracted from inventories elaborated in a single WWTP and based on a specific pilot system. In a sense, different results could be obtained in other situations. However, the results show some new perspectives to promote the environmental sustainability associated with biogas and sludge integrated management from UASB reactors. Besides, the LCA approach can be used in other similar WWTPs.

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