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Evaluation of the environmental life cycle of an STP that employs a low-rate trickling filter as post-treatment of a UASB reactor and different sludge-management alternatives

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ABSTRACT

This study aimed to undertake an environmental life cycle assessment (LCA) of a sewage treatment plant (STP) equipped with low-rate trickling filters (TFs) as post-treatment of upflow anaerobic sludge blanket (UASB). The STP is located in South Brazil and uses landfill and agriculture as sludge-disposal alternatives. The evaluation was performed using the LCA technique and SimaPro® 9 software. The results revealed that the gases methane (CH_4) and sulfur dioxide (SO_2), emitted into the atmosphere after the partial burning of the biogas in flares, are mainly responsible for impacts in the categories of global warming (GW) and terrestrial acidification (TA), respectively. Due to the low rate of hydraulic sewage application in TFs, nitrous oxide (N_2O) emissions stood out due to their high impact in the category of stratospheric ozone depletion (SOD). The use of sludge in agriculture obtained a greater potential for environmental impact compared to landfills in five of the eight categories evaluated. The main impacts of agricultural use were in the category of human toxicity (HT), due to the high concentration of zinc present in the sludge, and in the category TA, due to the emission of ammonia (NH_3) during hygienization of the sludge. In turn, the main positive aspects were avoided products, such as urea, phosphate fertilizer and limestone. The results contribute to a greater discussion of sewage-treatment processes, as well as sludge-management alternatives used in developing countries.

Keywords: alkaline stabilization, biogas, biological sludge, environmental assessment, nitrogen dioxide, sanitary landfill.

Avaliação do ciclo de vida ambiental de uma ETE que emprega filtro biológico percolador, de baixa taxa, como pós-tratamento de um reator UASB e diferentes alternativas de gerenciamento de lodo

RESUMO

O presente estudo teve por objetivo realizar a avaliação de ciclo de vida (ACV) ambiental de uma estação de tratamento de esgoto (ETE), dotada de filtros biológicos percoladores (FBPs) de baixa taxa, como pós-tratamento de reatores anaeróbios - UASB. A ETE está localizada no sul do Brasil e emprega como alternativas de destinação do lodo o aterro sanitário e o uso agrícola. Para realizar a avaliação, utilizou-se a técnica de ACV, empregando o software SimaPro® 9. Os resultados evidenciaram que os gases metano (CH_4) e dióxido de enxofre (SO_2), emitidos para a atmosfera, após a queima parcial do biogás em queimadores abertos, são os principais responsáveis pelos impactos nas categorias de mudanças climáticas (GW) e acidificação terrestre (TA), respectivamente. Devido à baixa taxa de aplicação hidráulica de esgoto nos FBPs, as emissões de óxido nitroso (N_2O) se destacaram pelo elevado impacto na categoria de depleção de ozônio estratosférico (SOD). O emprego do lodo na agricultura obteve um maior potencial de impacto ambiental, em relação ao aterro sanitário, em 5 das 8 categorias avaliadas. Os principais impactos do uso agrícola foram na categoria de toxicidade humana (HT), devido à elevada concentração de zinco presente no lodo, e na categoria de acidificação terrestre (TA), em virtude da emissão de amônia (NH_3) durante a higienização do lodo. Por sua vez, os principais aspectos positivos foram os produtos evitados como ureia, fertilizante fosfatado e calcário. Os resultados reportados contribuem para uma maior discussão dos processos de tratamento de esgoto, bem como de alternativas de gerenciamento de lodo, empregados em países em desenvolvimento.

Palavras-chave: aterro sanitário, avaliação ambiental, biogás, dióxido de nitrogênio, estabilização alcalina, lodo biológico.

1. INTRODUCTION

Population growth in Latin America and the Caribbean (LAC) has surpassed the capacity of national and local governments to meet the demand for basic sanitation services, especially those inherent in the collection and treatment of sewage (Noyola *et al.*, 2012). In Brazil, recent data from Agência Nacional de Águas (ANA; National Water Agency) confirm this problem by disclosing that the sanitary sewage collection rate in the country is 61.4%, and that only 42.6% of all sewage generated is treated (ANA, 2017). These data indicate that approximately 65 million Brazilians still do not have access to a collective system to remove sewage, and about 97 million do not have the sewage from their homes treated. Therefore, new sewage treatment plants (STPs) and the expansion of the capacity and treatment level of existing STPs should be planned in the coming years, since the intention is to universalize sewage servicers in the country.

One of the sewage technologies that should continue to be widely used in Brazil is that of upflow anaerobic sludge blanket (UASB) rectors. Present in 1,047 STPs, UASB reactors represent the most used treatment technology in the country (ANA, 2017). This is mainly due to low costs of implementation and operation compared to aerobic treatment systems (Chernicharo *et al.*, 2018). In addition, UASB reactors are responsible for the production of biogas, which is endowed with energy potential because it contains methane (CH_4) in its composition and can therefore be used for energy purposes within the treatment plant itself (Moran *et al.*, 2010). However, it should be noted that most Brazilian STPs collect biogas and conducted it to flares, in order to reduce rates of greenhouse gas emissions (Amaral *et al.*, 2018; Possetti *et al.*, 2019), since CH_4 has a global warming potential 34 times greater than that of carbon dioxide (CO_2) (IPCC, 2014). An additional aim of burning biogas is to reduce problems related to bad odors and equipment corrosion due to hydrogen sulfide (H_2S) present in the medium (Possetti *et al.*, 2018). However, if H_2S destruction occurs in low-efficiency burners, sulfur dioxide (SO_2) may form in the atmosphere (Possetti *et al.*, 2018).

Despite the recognized advantages, it should be emphasized that exclusive use of UASB reactors may be insufficient to meet legal requirements for discharging effluents into bodies of water (Almeida *et al.*, 2018). Thus, aerobic treatment processes, such as activated sludge and, mainly, trickling filters (TFs), are being used in Brazil as a stage for post-treatment of effluents from UASB reactors. The efficiency of removing organic matter in TFs systems can vary according to the hydraulic rate applied to its surface, or even the organic load applied to the volume of the percolating filter media, thus resulting in three possible types of TFs: low rate (1 to 4 $m^3.m^{-2}.d^{-1}$ or 0.08 to 0.4 $kgBOD.m^{-3}.d^{-1}$), intermediate rate (4 to 10 $m^3.m^{-2}.d^{-1}$ or 0.4 to 0.48 $kgBOD.m^{-3}.d^{-1}$) and high rate (10 to 40 $m^3.m^{-2}.d^{-1}$ or 0.48 to 1.0 $kgBOD.m^{-3}.d^{-1}$) (Metcalf & Eddy, 2016).

Low-rate TFs have an organic removal efficiency of more than 80%, with high effluent nitrification capacity (Corrêa, 2019). Although nitrification reduces the environmental problems intrinsic to the discharge of effluents into water bodies, it should be emphasized that it is responsible for the production of nitrous oxide (N_2O) (Vasilaki *et al.*, 2019), which has a global warming potential 265 times greater than CO_2 (IPCC, 2014). Still, TFs can also be a source of CH_4 emissions, since up to 40% of this biogas remains dissolved in the effluent of the UASB reactors and can be released in the post-treatment stage (Souza *et al.*, 2011). Within this context, STPs that employ UASB reactors followed by low-rate TFs can become a significant source of CH_4 and N_2O (El-Fadel e Massoud, 2001). Studies referring to the assessment of environmental impacts of systems composed of UASB reactors followed by low-rate TFs are incipient (Bressani-Ribeiro *et al.*, 2017), and there is still no integrated discussion of the environmental problems inherent to these two treatment technologies.

In addition to the issues of gaseous emissions arising from sewage treatment, another by-product generated by STPs that can bring a series of significant environmental impacts is sludge (Amaral *et al.*, 2019). Characterized by high concentrations of nutrients and organic matter, sludge can be used as a fertilizer in agriculture (Bittencourt, 2014; Cieslik *et al.*, 2015). However, sludge also has high levels of water and pathogenic microorganisms and, thus, processes of dewatering and hygienization must be performed for its use as a biofertilizer (Lobato *et al.*, 2018). A practice adopted by some sanitation companies in Brazil is to dewater sludge, in drying beds or in centrifuges, followed by prolonged alkaline stabilization (PAS).

The process of PAS consists of raising the pH of the sludge to 12 for a minimum period of 2 hours by the application of chemical products, such as lime, for example. The mixture must be sufficient to ensure that the entire mass of the sludge in contact with the lime suffers an increase in pH (USEPA, 1992). It should be noted that during this process there is a release of ammonia (NH_3), which is another significant point of emission in an STP that employs such a procedure (Amaral *et al.*, 2019). After the mixing step, the sludge must be sent to a curing and storage yard, where it will remain for a period of 35 to 45 days (Andreoli *et al.*, 2014). Despite being considered a recognized practice worldwide, the agricultural destination of sewage sludge is performed by few sanitation companies in Brazil. This is mainly due to the difficulty that these companies have in meeting the criteria and procedures established by Brazilian legislation for agricultural use (Bittencourt *et al.*, 2014). Thus, the main destination of the sludge produced in Brazilian STPs remains the sanitary landfill. Studies of environmental impacts resulting from sludge disposal alternatives in developing countries (Hernandez-Padilla *et al.*, 2017; Amaral *et al.*, 2018), whether in agricultural areas or landfills, are also incipient.

Based on the understanding of the need for new studies based on the survey of environmental impacts in STPs, it should be emphasized that the development of inventories, as well as the application of decision-making tools such as the Life Cycle Assessment (LCA), are fundamental for the identification of strategies to mitigate environmental impacts and in the choice of environmentally correct alternatives for sewage treatments and final disposal of sludge. In this context, the objective of this article was to carry out an environmental LCA of an STP that employs UASB reactors followed by low-rate TFs, with the a primary focus on CH_4, H_2S, N_2O and NH_3 emissions to the atmosphere, as well as on comparing environmental impacts between the sludge disposal alternatives of landfills and agricultural areas.

2. MATERIALS AND METHODS

2.1. Study area

To meet the objective of the present study, a small STP located in the South Region of Brazil, was used as a study area. With a capacity to treat sewage of a population of up to 52 thousand inhabitants, the plant has a design flow equal to 90 L.s^{-1}. The treatment system adopted at the STP, consists: preliminary treatment (course and fine screens, grit chamber and a Parshall flow meter); 03 (three) UASB reactors; 02 (two) low-rate TFs and 02 (two) circular secondary decanters. To maintain the active biota in the biofilm during periods of low flow (dawn, for example), the effluent from the TFs is recirculated. More detailed information about the UASB reactors and the TFs implanted in the studied STP are shown in Table 1.

Table 1. Characteristics of the UASB reactors and the TFs implanted in the STPs under study.

Parameters	UASB reactors	TFs
Population (inhab)	34,000 (52,000)*	
Flow rate (L.s^{-1})	33 (90)*	
Hydraulic retention time (h)	11.3 (8.0)*	–
Volumetric organic load (kgBOD.m^{-3}.d^{-1})	0.8	0.1 – 0.4
Volumetric hydraulic load (m^3.m^{-2}.d^{-1})	–	1 – 4
Number of reactors	3	2
Type	Trunk-conical	Circular
Diameter of each reactor (m)	18	22
Useful depth of each reactor (m)	5.75	3.0
Useful volume of each reactor (m^3)	800	1,140

* Values in parentheses refer to design parameters.

The waste produced in the preliminary treatment (waste from the screens and grit chamber) is sent to a landfill. The sludge from the UASB reactors and secondary decanters is directed to cover conventional drying beds. After the dewatering process, the sludge is sent for hygienization in a Sludge Management Unit (SMU) for the PAS process to be carried out. After the curing period, the sludge can be made available for agricultural areas. In sporadic situations, after the dewatering process in the drying beds, the sludge can be sent to a sanitary landfill without the need, therefore, for the hygienization step. Finally, the biogas produced in the UASB reactors is collected and conducted to flares with low CH_4 destruction efficiency.

2.2. Elaboration of environmental inventories for LCA

The elaboration of environmental inventories of the domestic sewage treatment processes, as well as the sludge management alternatives used in the STP, took place through the use of primary (measured) and secondary (bibliographical references/data of Ecoinvent® database) data of parameters correlated with the gaseous, liquid and solid phases of the STP (Figure 1). The chosen functional unit for the study was the treatment of 1 m^3 of sewage. Another parameter considered in the study was the consumption of electricity in the treatment plant. These data were obtained directly from the sanitation company responsible for the STP.

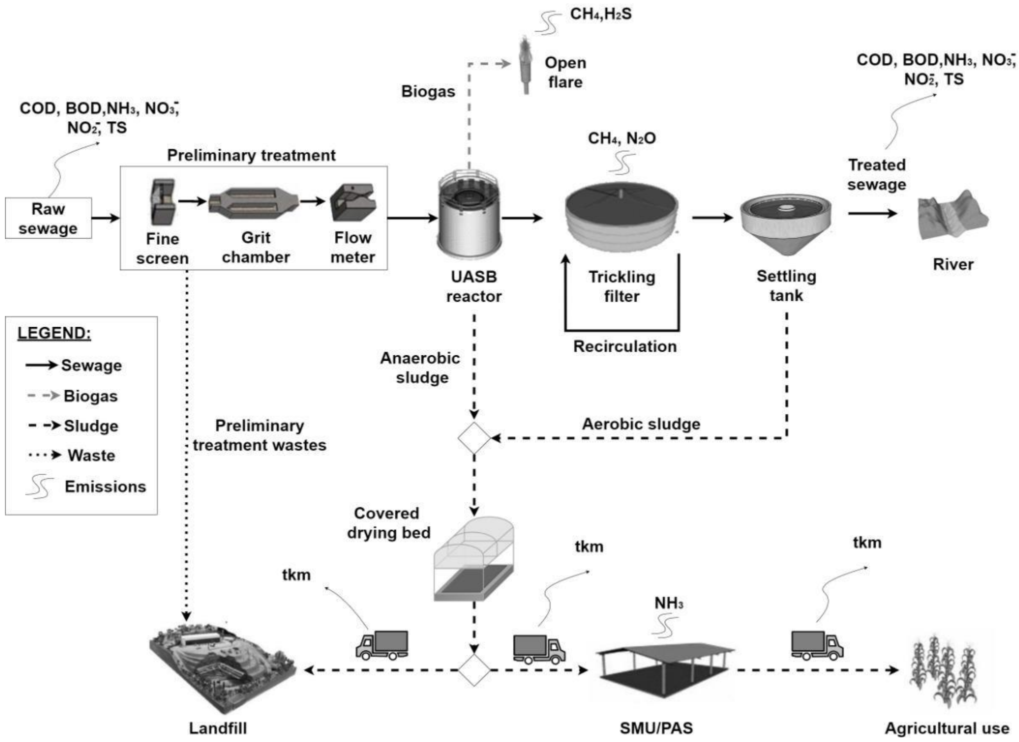

Figure 1. Schematic diagram of the gaseous, liquid and solid phases in the STP under study.

2.2.1. Gaseous phase

Environmental inventory of the gaseous phase included the following: flow and characterization of the biogas produced in the UASB reactors; efficiency of flares with respect to the destruction of CH_4 and H_2S; emission rates of N_2O and CH_4 in TFs; and emissions of NH_3 during PAS of the sewage. The study also took into account emissions related to the transportation of lime to the STP (for the PAS process), the transportation of sludge to the agricultural area or sanitary landfill, and the process of applying the sanitized sludge to the agricultural area.

The flow of biogas produced in the UASB reactors was calculated using ProBio 1.0 *software* (2021). The input data required by the *software* were sewage flow and chemical oxygen demand (COD) affluent to the UASB reactors. These data were obtained from the STP and refer to average values found during 2018. The values reported by Lobato *et al.* (2012) were used for biogas composition, being, in volumetric relations ($v.v^{-1}$), equal to: 70% for CH_4 and 1,500 ppm for H_2S. The destruction efficiency for CH_4 and H_2S in flares was obtained through studies carried out by Kaminski *et al.* (2018). According to these authors, this type of burner has a destruction efficiency, on average, for these gases of 50%.

Regarding emissions of N_2O and CH_4 in the TFs of the STP, the reference values of a domestic sewage treatment system of the constructed vertical *wetland* type were used (Fuchs *et al.*, 2011; Gutierrez, 2014). It should be noted that the adoption of these values was due to the hydraulic similarity between the systems and also due to the fact there are no emission data in literature for N_2O and CH_4 in TFs at full scale. Thus, emissions of 2.68 $gCH4.m^{-3}{}_{sewage}$ and 0.23 $gN2O.m^{-3}{}_{sewage}$ in TFs were considered. The NH_3 emission value, in the PAS of sludge, was obtained from studies carried out by Amaral *et al.* (2018), who found an average emission value of 1.2 $gNH_3.m^{-3}{}_{sewage}$. Emissions related to the transportation of lime to the STP, as well as the destinations of the waste from the preliminary treatment and the dewatered sludge, whether an agricultural area or landfill, were reported according to the parameter tkm, which considers the mass transported (in tons) and the distance covered (round trip in kilometers). Finally, emissions related to the application of sludge in agriculture areas followed the models presented by Nemecek and Schnetzer (2011), according to the study of Amaral *et al.* (2018).

2.2.2. Liquid phase

Environmental inventory of the liquid phase considered the following parameters for the influent and effluent of the STP: COD, biochemical oxygen demand (BOD_5), NH_3, nitrate (NO_3^-), nitrite (NO_2^-) and total solids (TS). Collections were performed at these points during two 24-hour sampling campaigns in the years of 2017 and 2018. The analyses followed the procedures established in *Standard Methods for the Examination of Water and Wastewater* (Apha *et al.*, 2012).

2.2.3. Solid phase

The amount of waste from the preliminary treatment was obtained from the monthly average of 2018 in the STP. The amount of total solids (TS) in the biological sludge from the UASB reactors and the TFs was estimated from the COD applied at the STP. For this, the production of TS in UASB reactors followed by aerobic-post-treatment was used, which is 0.25 kgST.kgCOD applied (Andreoli *et al.*, 2014).

The environmental inventory of the hygienized sludge application process in agricultural areas took into account the models reported by Nemecek and Schnetzer (2011). The input data required for the modeling were: nitrogen (N) and phosphorus (P) content in the hygienized sludge, characteristics of the soil where the sludge is to be disposed and the products avoided by the agricultural use of the sludge. Thus, the levels of N and P used were 10.2 $g.kg^{-1}$ and 3.6 $g.kg^{-1}$, respectively. The soil type considered was Haplic Cambisol with its specific characteristics of clay content, organic carbon content and the amount of eroded soil. For the application of hygienized sludge in the agricultural area, urea (with 45% nitrogen content), phosphate fertilizer (P_2O_5) and limestone were considered as avoided products. This step used the characterization data for hygienized sludge reported by Amaral *et al.* (2018).

Data relating to the manufacture of products avoided in agricultural use, the manufacture of polymer (used for dewatering), the manufacture of lime, the type of transport by motor vehicles and the production of diesel for fuel and electricity generation were obtained through the Ecoinvent® database. For lime, Relative Power of Total Neutralization (RPNT) of 75% was considered, while a RPNT of 110% was considered for lime (contained in biological sludge) (Bittencourt, 2014). Finally, since there are no specific environmental inventories of impacts related to sludge deposited in landfills, the present study used data of environmental inventories of a landfill that receives sludge from the paper industry. This consideration was made due to the composition and biodegradability of this material being closer to those of STP sludge used in Brazilian landfills.

2.3. Assessment of environmental impacts

The environmental impact was calculated using the LCA methodology and SimaPro® 9 *software*. The method used was ReCiPe 2016 Midpoint (H). The assessed impact categories were: global warming (GW), stratospheric ozone depletion (SOD), ozone formation - terrestrial ecosystems (OTE), terrestrial acidification (TA), aquatic eutrophication (fresh water) (EUT-AW), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FWE) and human toxicity – non cancer (HT).

3. RESULTS AND DISCUSSION

3.1. Environmental inventory of the processes used in the STP

Table 2 shows the environmental inventory of the flows, into and out, of the phases (gaseous, liquid and solid) referring to the sewage treatment processes (preliminary treatment, UASB reactors, TFs, secondary decanters) and the different sludge management alternatives (destination for landfill or agricultural area) employed at the studied STP.

Samples of sewage affluent to the STP had values within the ranges for typical concentrations of domestic sewage found in the literature (Aisse, 2002; Von Sperling, 2014). The average efficiency of the STP for removing COD and BOD_5 was over 87%. For the nitrification process, the average reduction of NH_3 in the TFs was 43%. Similar results were obtained by Lopes *et al.* (2018) in vertical *wetlands* as a post-treatment step for UASB reactors. The estimate of biogas production in the UASB reactors was 341 $m^3.d^{-1}$. Considering the lower calorific power (LCP) of CH_4 equal to 9.9 $kWh.m^{-3}$, the chemical potential that could be used in the STP would be approximately 3,376 $kWh.d^{-1}$. This potential is not greater, due to fugitive emissions in the reactor and the CH_4 not recovered in the biogas, that remains dissolved in the treated effluent. According to Souza *et al.* (2011), concentrations of 17 to 22 $mg.L^{-1}$ of CH_4 can be found in liquid medium. Regarding the destination of the sludge, it should be noted that the distance from the STP to the SMU, and from this to the agricultural area, increased the parameter of tkm by approximately two times in relation to disposal in landfill.

Table 2. Inventory of the Life Cycle of processes used in the STP.

Inputs (Pollutants in domestic wastewater)	**Concentration ($mg.L^{-1}$)**	**Correlated to functional unit**
Chemical oxygen demand (COD)	565.0	0.565 $kg.m^{-3}$
Biochemical oxygen demand (BOD)	293.0	0.293 $kg.m^{-3}$
Unionized ammonia (NH_3 - N)	65.7	0.066 $kg.m^{-3}$
Nitrate (NO_3^- - N)	1.2	0.0012 $kg.m^{-3}$
Nitrite (NO_2^- - N)	0.2	0.0002 $kg.m^{-3}$
Input (energy)	**Demand ($kWh.d^{-1}$)**	**Correlated to functional unit**
Electricity consumed	1,086.5	0.38 $kWh.m^{-3}$
Emissions to water (final treated effluent)	**Concentration ($mg.L^{-1}$)**	**Correlated to functional unit**
Chemical oxygen demand (COD)	68.0	0.068 $kg.m^{-3}$
Biochemical oxygen demand (BOD)	17.0	0.017 $kg.m^{-3}$
Unionized ammonia (NH_3 - N)	37.5	0.0375 $kg.m^{-3}$
Nitrate (NO_3^- - N)	9.0	0.009 $kg.m^{-3}$
Nitrite (NO_2^- - N)	5.0	0.005 $kg.m^{-3}$
Total solids (TS)	19.0	0.019 $kg.m^{-3}$
Biogas production in UASB reactors	**Flow rate ($m^3.d^{-1}$)**	**Correlated to functional unit**
Biogas (70% – CH_4 and 1,500 ppm – H_2S)	341.1	
Emissions to air	**Flow rate ($m^3.d^{-1}$)**	**Correlated to functional unit**
Methane (CH_4)[a]	119.4	0.042 $m^3.m^{-3}$
Hydrogen sulfide (H_2S)[a]	0.26	0.00009 $m^3.m^{-3}$
Nitrous oxide (N_2O) – Trickling filter		0.23 $g.m^{-3}$
Methane (CH_4) – Trickling filter[b]		2.68 $g.m^{-3}$
Solid waste	**Production ($kg.d^{-1}$)**	**Correlated to functional unit**
Preliminary treatment waste	82.6	0.029 $kg.m^{-3}$
Dewatered sludge	500.0	0.17 $kg.m^{-3}$
Solid waste transportation	**Mass x distance (tkm)**	**Correlated to functional unit**
Preliminary treatment waste – Landfill		0.0033 $tkm.m^{-3}$
Dewatered sludge – Landfill		0.066 $tkm.m^{-3}$
Dewatered sludge – Agricultural area		0.01412 $tkm.m^{-3}$

[a]Considering an efficiency of 50% destruction in the flare; [b]Methane dissolved ($CH_{4\ dissolved}$) in the UASB reactor effluent emitted in the Trickling filter.

3.2. Environmental assessment of the STP with sludge being destined to landfill

Figure 2 shows the contribution of each process used in the STP to the impact categories evaluated for the landfill sludge disposal scenario. The biggest contribution to the GW category, with a 53% influence, was the stage of burning the CH_4 produced in the UASB reactors. Due to the low efficiency of flares (~50%), a significant portion of CH_4 is still emitted into the atmosphere. With a CH_4 flow rate equal to 238 $m^3.d^{-1}$ in the UASB reactors (70% in relation to biogas), it is calculated that 119 $m^3.d^{-1}$ of this gas is emitted into the atmosphere by the burners. Considering a density of 0.657 $kg.m^{-3}$ and a global warming potential 34 times higher than CO_2, the flow of CH_4 emitted corresponds to an average rate of greenhouse gas emissions of approximately 1,000 $tCO_2eq.year^{-1}$. The TFs and the final effluent of the STP are also considered to be CH_4 emission sources, contributing about 25% of the impacts to the GW category. Finally, the sending of sludge to landfill contributed about 14% to the environmental impacts that occurred in the GW category. This percentage is associated with CH_4 and CO_2 produced during the degradation of this material in landfill cells.

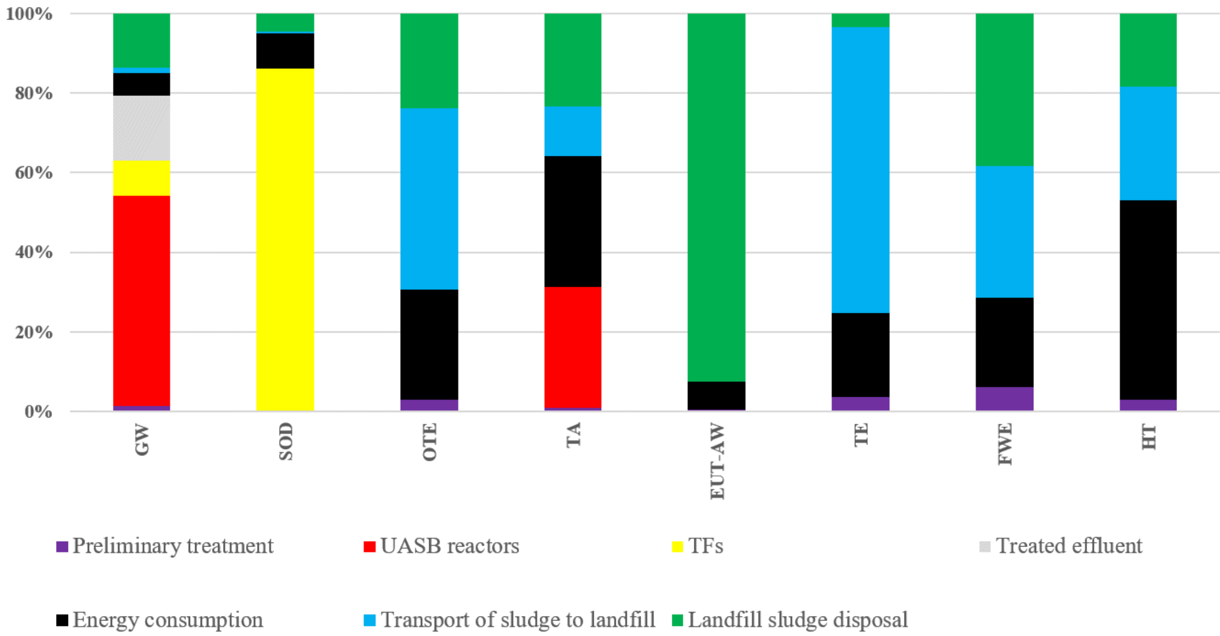

Figure 2. Contribution of each treatment step in the categories of environmental impacts evaluated considering the destination of sludge in landfill.

The process with the greatest influence on the SOD category was the TFs (86%) due to N_2O emissions. In the stratosphere, N_2O plays an important catalytic role in the consumption of stratospheric ozone (O_3), having a residence time in the media of up to 120 years (Ravishankara *et al.*, 2009). One way to reduce the impacts caused by the emission of this gas in TFs is to carry out more adequate control of the aeration process. It should be noted that the alternative of sending the sludge to landfill contributes only about 5% to the environmental impacts of the SOD category.

The process of transporting sludge to landfills had an approximately 45% influence on the impacts caused in the OTE category. This is mainly due to emissions of nitrogen oxides (NO_x) from the use of diesel as a fuel in motor vehicles. NO_x is a major contributor to increased ozone concentration on the Earth's surface, which in turn contributes to the worsening of air pollution in cities and acid rain (Quiros *et al.*, 2017). As for OTE, the TE category also had the transport of sludge to the landfill as the main environmental impact process, with an influence of approximately 72%. This influence is due to copper (heavy metal) emissions resulting from wear and tear on brakes in motor vehicles. Vehicle brake systems are made up of brake pads composed mainly of copper fibers. The pad, when forced by the rotating brake disc, generates wear on the fibers causing the emission of copper (Simons, 2013). Tire wear during the sludge transport process was one of the main factors responsible for the impacts measured in the FWE category. Still, for this category, zinc present in landfill leachate contributed approximately 40% of the impacts.

The most impactful process in the TA category, with a 30% influence, was the emission of sulfur dioxide (SO_2) and H_2S in the burners of the UASB reactors. As the burners are unable to fully combust the biogas, SO_2 is formed and emitted into the atmosphere. The transportation and disposal of sludge in landfills had an influence of about 36% on the TA category. This is also due to SO_2 (produced during sludge transport due to the possibility of incomplete burning of diesel).

The process that contributed most to the EUT-AW category was the destination of sludge in landfills, with 92%. This is due to the high presence of phosphate (PO_4^{3-}) in the leachate in the landfill. The inventory used considered the emission of 0.437 $gPO_4^{3-}.kg^{-1}$ of waste to the river and 0.272 $gPO_4^{3-}.kg^{-1}$ to groundwater. In the HT category, the processes of transportation and disposal of sludge in landfills had an influence of approximately 50%.

3.3. Environmental assessment of the STP with sludge destined for agriculture use

Figure 3 shows the contribution of each process used in the STP considering sludge disposal in agriculture. For the GW category, CH_4 emissions to the atmosphere in the UASB reactors, TFs and final effluent remain the main sources of environmental impact. Sludge transport and final destination for agriculture only had a 5% influence on this category. In turn, the agricultural use of sludge was responsible for approximately 80% of the impacts in the TA category, which is mainly due to the emission of NH_3 in the PAS process. Although the application of lime raises the pH in the sludge, ensuring the reduction of pathogenic microorganisms (Bittencourt, 2014), this process also causes a significant amount of NH_3 to be volatized.

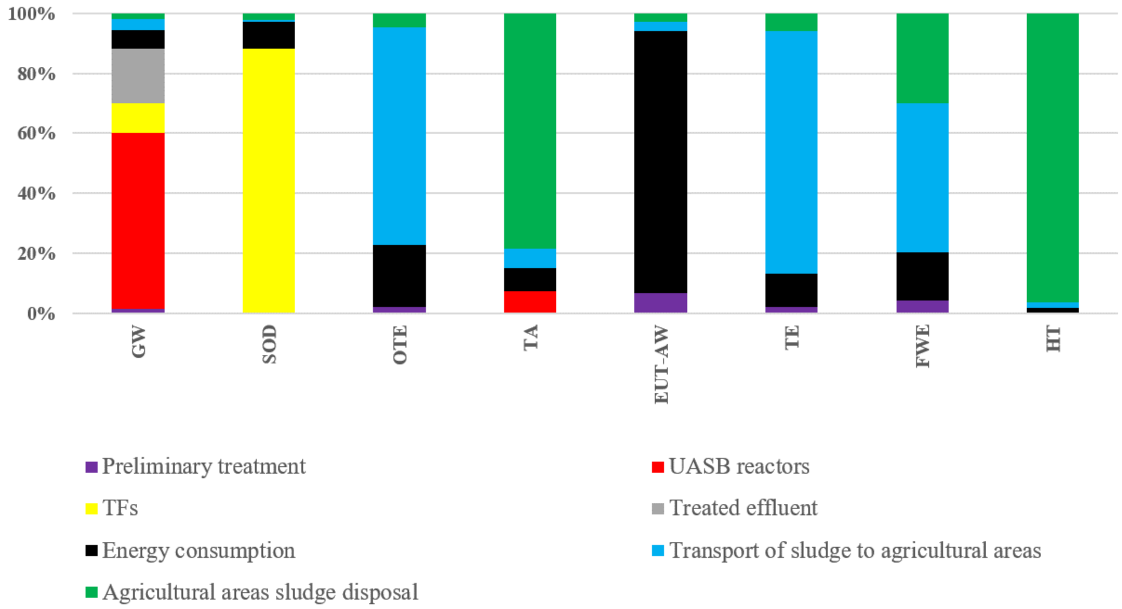

Figure 3. Contribution of each treatment step in the categories of environmental impacts evaluated considering the destination of sludge in agricultural areas.

In the SOD category, N_2O emissions in TFs continued to be the main contributor responsible for the measured environmental impacts. The destination of sludge in agriculture was responsible for only 3% of the impacts caused in this category. Sludge transport was responsible for contributing approximately 70% of the impacts caused in the OTE category (due to NO_x emissions form the use of diesel) and 80% of the impacts in the TE category (due to copper emissions).

The transport and use of sludge in the agricultural area were responsible for about 80% of the impacts measured in the FWE category. With regard to transport, tire wear was the main source of impact. In sludge application, the high concentration of zinc (heavy metal) in the sludge (514 $mg.kg^{-1}$) used in the present study, and reported by Amaral *et al.* (2018), was responsible for the impacts in this category. According to Kummer *et al.* (2018), zinc has a low potential for adsorption in soils and, thus, is easily leached into rivers and groundwater.

The avoided products (urea, phosphate fertilizer and limestone), due to the use of sludge in agricultural areas, contributed to this alternative, having an impact on the EUT-FW category of only 4%. Finally, in the HT category, the agricultural disposal of sludge was responsible for 95% of the environmental impacts, which was due to the high concentration of zinc (heavy metal) in the sludge. Results obtained by Yoshida *et al.* (2018) also highlighted the impact of the application of sludge containing a high concentration of zinc on the soil. According to these authors, zinc was responsible for 85 to 92% of the impacts caused in the HT category.

3.4. Comparative LCA

The absolute values of the contribution of each process used in the STP, with the different alternatives for final disposal of the sludge, are shown in Table 3. In general, the agricultural use of sludge obtained a greater potential for environmental impact in the following categories: OTE, TA, TE, FWE and HT.

The agricultural use of the sludge had a greater impact on the categories OTE, TE and FWE compared to destination in landfill due to the greater distances traveled to carry out the hygienization and disposal of the sludge, thus resulting in greater wear and tear on vehicle and also higher rates of NO_x and copper emissions into the atmosphere. In the TA category, NH_3 emissions during the PAS process were responsible for the greater impact of the agricultural use of sludge. As shown in Figure 3, of all the categories investigated, the one with the greatest impact from the agricultural disposition of sludge was HT, due to the high concentration of zinc in the sludge. This parameter has a characterization factor of 1.29×10^6 by the method used for emission in agricultural soil, which causes a great impact for this destination.

Table 3. Life Cycle Assessment of processes used in the STP.

Impact categories	Units	Transport		Disposal	
		Landfill	Agricultural areas	Landfill	Agricultural areas
GW	kg CO_2 eq	0.027	0.059	0.241	0.029
SOD	kg CFC11 eq	8.18×10^{-9}	1.75×10^{-8}	1.37×10^{-7}	5.99×10^{-8}
OTE	kg NO_x eq	1.83×10^{-4}	3.92×10^{-8}	9.64×10^{-5}	2.74×10^{-5}
TA	kg SO_2 eq	9.50×10^{-5}	2.03×10^{-4}	1.79×10^{-4}	2.54×10^{-3}
EUT-AW	kg P eq	3.24×10^{-8}	6.93×10^{-8}	2.63×10^{-5}	6.54×10^{-8}
TE	kg 1,4-DCB eq	6.84×10^{-5}	1.46×10^{-4}	3.27×10^{-6}	1.06×10^{-5}
FWE	kg 1,4-DCB eq	4.56×10^{-5}	9.75×10^{-5}	5.29×10^{-5}	5.90×10^{-5}
HT	kg 1,4-DCB eq	0.113	0.243	7.38×10^{-2}	12.69

4. CONCLUSIONS

The destination of sewage sludge for agriculture, under the conditions addressed here, had a greater potential for impact in five of the eight categories evaluated. It should be noted that in this article, for comparison purposes, a landfill from the Ecoinvent® database was used, which receives sludge form the paper and cellulose industry. The main impacts observed in the process of agricultural use of sludge are related to the concentration of zinc present, which significantly affects the FWE and HT categories. On the other hand, the main benefits of the agricultural use of sludge were avoided products, such as urea, phosphate fertilizer and limestone. The main impacts related to the disposal of sludge in landfills were limited to CH_4 emissions to the atmosphere and the PO_4^{3-} load present in the leachate. The results of the sewage treatment processes used in the studied STP showed the problem of CH_4 and N_2O emissions. With regard to CH_4, the use of burners with greater burning efficiency, as well as the use of energy from this gas, could lessen the impact on the GW category. In addition, the CH_4 dissolved in the effluent from the UASB reactors caused the TFs and the final effluent from the STP to become significant emission points. Emissions of N_2O in the low-rate TFs contributed the most to the SOD category. Finally, it is recommended that future studies carry out environmental inventories of emissions in landfills that receive sewage sludge and in low-rate TFs, as a post-treatment step for anaerobic processes.

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