Analyzing Faecal Sludge Treatment Plants' Life Cycle Carbon Footprint – a case of Zambia

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Abstract - Biogas technology has been widely used as an economical technology to manage and reduce carbon emissions of Faecal Sludge (FS) from pit latrines in developing countries. However, the carbon footprint of using this technology in faecal sludge treatment is not clearly quantified. This study aimed to close this gap by developing an Integrated Life-Cycle Carbon-Footprint Analysis (ILCCA) model for faecal sludge treatment plants (FSTPs) in developing countries, taking Zambia as a case. The annual carbon footprint and operational efficiency of two local FSTPs were investigated and analyzed. It was found that under the Zambian environmental and economic conditions, treating 1m^3 of faecal sludge produced about 18.41 kgCO$_2$e and 5.01 kgCO$_2$e of emissions for Kanyama and Chazanga, respectively. This also implied that to produce 1m^3 of biogas from pit latrine faecal sludge produced 2.53 kgCO$_2$e (Chazanga) and 10.31 kgCO$_2$e (Kanyama) of carbon emissions. The carbon emissions for Chazanga are within range of many previous studies. However, the result for Kanyama FSTP's (10.31 CO$_2$e) is significantly higher than the carbon emissions from previous studies - indicating a very poor environmental efficiency. This difference in the two plants is largely attributed to the differences in distances covered by the trucks transporting FS. It was also found that FS transportation from households to the treatment plant was the highest GHG emission phase for both plants, accounting for over 94% of the total emissions. This proved to negatively affect the gains made by the technology at the treatment plants in capturing GHG from the faecal sludge collected from pit latrines. However, the result further shows that the treatment process had the lowest carbon footprint as it captures GHG by producing biogas; indicating and confirming the positive role of using anaerobic digestion technology in waste treatment and recycling. The result of the study further indicates that eliminating or improving efficiency in the transportation of faecal sludge or placing the treatment plants as close to households as possibly safe could increase the environmental efficiency of the FSTPs by up to about 94%.

In terms of Energy Intensity, the results varied from 1.03 to 1.23 kWh/m^3, which is relatively energy-intensive. This implies therefore, that two plants cannot achieve energy balance by themselves. The annual energy balance for both plants was negative, i.e., -52,163 kWh for Chazanga and -36,946 kWh for Kanyama, with an energy self-sufficiency rate of 21.39% and 27.76% respectively. This study therefore, provides a clearer understanding of the FSTPs' vulnerabilities and weaknesses with regard to carbon emissions and operational efficiency, which can be a valuable tool to improve the overall performance of the FSTPs in similar countries and regions.

Keywords: Biogas, Carbon footprint, Efficiency, Faecal sludge plants, Greenhouse Gases.

I. INTRODUCTION

Biogas production from faecal sludge has widely been used as an economical technology for managing and reducing carbon emissions of Faecal Sludge (FS) from pit latrines in developing countries. However, the environmental impact of biogas systems, particularly their carbon footprint, during faecal sludge treatment has been widely contested in scientific circles for many years. While many studies have been conducted on using this technology for treating other substrates such as crop residuals and wastewater from industries, there is limited empirical data to ascertain its carbon footprint and environmental sustainability when used for this purpose.

Faecal sludge (FS) refers to the liquid and semi-liquid waste (mostly human excreta) collected mainly from onsite sanitation facilities such as pits latrines (Hemkend-Reis et al., 2008). With the growing global population and urbanization, there has been a rapid increase in the production of human excreta-related sludge (Xu et al., 2021). On the other hand, pit latrines are a vital part of public health initiatives. They are an essential type of decentralized excreta management, providing low-cost sanitation to around a fourth of the world's total population, especially in developing countries (Reid et al., 2014). As a result of most African countries' inability to install reticulated sanitation systems due to financial costs, poor city planning and rapid urbanization, meeting the "Universal Access to Sanitation by 2030" goal implies the construction of more pit latrines. For instance, in the capital city of Zambia, Lusaka, more than 90% of the people use pit latrines in the peri-urban areas (Simwambi et al., 2017). As a result, pit latrines are the predominant source of faecal sludge not only in Lusaka but many other cities in developing countries.

According to van Eekert et al. (2019), using pit latrines would increase the amount of greenhouse gas emissions from this source two-fold. This is because the anaerobic breakdown of faecal sludge in pits latrines is a substantial source of the greenhouse gas Methane (CH_4) (Reid et al., 2014). They produce 4.0 million metric tonnes of CH_4 per year, amounting to 112 Mt CO_2e (van Eekert et al., 2019). In some countries, greenhouse gasses account for as high as 25% of anthropogenic CH_4 emissions, as in the case of Bangladesh. In comparison, many African countries range from 5% to 10% (EPA, 2012), which injures both public health and the climate.

To solve this problem, many governments and international organizations have been employing biogas technology. It has been widely used especially in developing countries by treating faecal sludge collected from pit latrines. This is especially true for Sub-Saharan Africa, which is expected to continue relying on pit latrines to provide sanitation to its population in the near future.

In Zambia, for example, two Faecal Sludge Treatment Plants (FSTP) using biogas technology have been built in two of the most densely populated peri-urban areas of Lusaka city solely for this purpose. This is based on the advantages of small space, low capital and maintenance cost requirements associated with biogas technology. Another advantage is its ability to not only treat human excreta with GHG capturing but also produce renewable energy which can substitute fossil fuels (Chen et al., 2010; Chen et al., 2018; Kougias and Angelidaki, 2018). Therefore, the expected increase in latrines also implies that installing faecal sludge treatment plants using this technology will be on the rise.

While biogas technology is well-known for its advantages, its climatic benefits are not extensively measured or are at least inconsistent. Bruun et al. (2014) suggest that they could have the same climatic impacts as the fossil fuels they desire to replace. This is owing to some high energy-consuming and GHG-emitting steps in this technology (Jurić and Ljubas, 2020). This may affect its carbon footprint, environmental performance, and contribution to climate change. One effective way, in which producers and processors can tackle the challenge of climate change, is by lessening their carbon footprint (Finnegan et al., 2017) as low as possible. This, therefore, requires urgent mitigation measures to manage emissions from this technology.

It is widely accepted that "you cannot manage what you cannot measure." Thus, before suggesting any particular mitigation measures, Reid et al. (2014) suggest that it is important to quantify the Carbon footprint of such sanitation systems with superior certainty. According to the literature reviewed, studies to quantify the Carbon Footprint of biogas plants that solely treat faecal sludge emptied from pit latrines are yet to be conducted. Previous studies, such as those by Lijó et al. (2014), Ishii and Boyer (2015), Fuchsz and Kohlheb (2015) and Ertem et al. (2016), have been conducted in industrialized continents such as Europe using the Life Cycle Analysis (LCA) approach. Similar studies, such as Cornejo et al. (2013) and Lam et al. (2015) have also been conducted in developing countries.

However, no previous research findings can be used to evaluate the environmental effects of a faecal sludge treatment facility in Zambia. Firstly, because most previous research did not consider quantifying the carbon footprint of such a plant, while some studies were conducted on onsite biodigesters connected to the latrines or wastewater treatment plants. Additionally, majority of these tended to focus more on systems utilizing crop residuals and wastewater as feedstock. High carbon footprint potential process parameters such as faecal sludge transportation from households to the treatment plant were also not included. Secondly, in most situations, the effects on environmental efficiency, at least in their numerical sense, cannot be correlated to other places explicitly due to the vast number of variables and variations in social, economic, and environmental constraints between regions and countries (Hijazi et al., 2016). Thirdly, most research has used ordinary Life Cycle Assessment (LCA) to determine the environmental impacts of similar plants.

Despite the valuable data produced by LCA studies in the realm of wastewater treatment and biogas production, literature has highlighted several limitations of the tool to solely be used for assessing and selecting technologies. The primary limitations are that the previous LCA studies lack an operational assessment of treatment plants in terms of effectiveness, efficiency and suitability of operational practice (Silva et al., 2014). They also fail to provide comprehensive and essential information on the complexity of such systems (Cassidy et al., 2020), especially in developing countries. This has sometimes given the impression that the lowest system's carbon footprint means the "most sustainable" when the system or technology could have a very low operational efficiency which can also make the system or technology very unsustainable. To close all these gaps, the study intended to improve the life cycle carbon footprint analysis of using biogas technology in developing countries, taking the two FSTPs in Zambia as a case.

Therefore, to also better represent a systematic picture of the FSTPs' life cycle, an Integrated Life-cycle Carbon-footprint Analysis (ILCCA) model was proposed and utilized in this study as shown in **Figure 2**. The model used a holistic approach by simultaneously assessing the plants’ Environmental Efficiency (Carbon Footprint) by employing LCA principles and the plants’ Operational Efficiency by including efficiency indicators to better understand the FSTPs. Understanding this would provide the guidance required for developing a benchmarking tool for improving the performance of FSTPs and act as essential references for establishing similar plants in other developing countries.

II. MATERIALS AND METHODOLOGY

The study was conducted at the Faecal Sludge Treatment Plants (FSTP) plants - Kanyama and Chazanga in Zambia’s largest city Lusaka (CSO, 2013). Though they utilize the same treatment technology, both plants were included in the study as they were in the same city and the only plants solely established to treat FS in Zambia with a distance of about 20km apart. However, despite these similarities, the two treatment plants had significant differences that could have affected their environmental performance such as the differences in total population serviced, plant sizes and the distances covered by trucks transporting faecal sludge. The plants are both owned by the government through the Lusaka Water and Sanitation Company. The FSTPs are as described by SNV and ISF-UTS (2021). They were built specifically to treat FS discharged from pit latrines. The Kanyama plant serves 250,000 people with a service radius of 25km, while the Chazanga plant serves about 200,000 with a service radius of 15km. They were founded in 2012 and 2014 respectively and operated daily throughout the year.

The two plants had identical operating and flow processes. Each facility contains a fixed-dome biogas digester (biodigester). The biodigester uses anaerobic digestion as the method of treatment with the Kanyama FSTP's biodigester measuring 58 m^3 and the Chazanga's biodigester measuring 50 m^3 (See Table *1*). They had a daily sludge treatment capacity of 6.3 m^3 (Kanyama) and 7.0 m^3 (Chazanga).

The process starts with the collection of FS from household latrines. This is mostly done manually using buckets and hoes due to the high presence of solid waste and grit. However, semi-automated machines are sometimes used when the faecal sludge contains less solid waste. The FS is then packed in 60-liter burels and transported to the treatment plants in open medium-heavy-duty trucks.

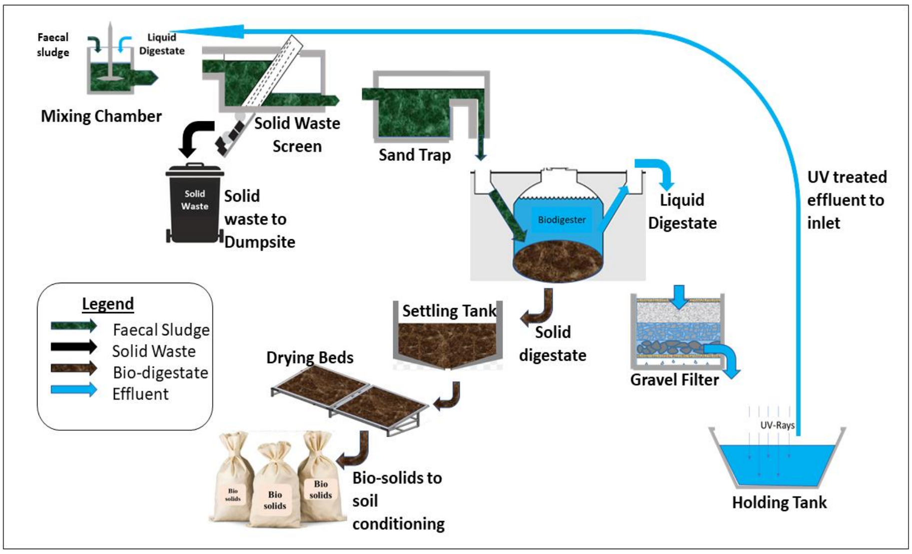


Figure 1: General treatment process layout at both Kanyama and Chazanga FSTPs.

At the plants, as illustrated in Figure 1, solid waste is separated from sludge using bar screens. As sludge enters the biogas digester, sand and grit from the sludge are caught in sand traps. After treatment, produced biogas collects at the top of the dome-shaped biodigester where about half of it is used for cooking by employees within the plant. The remainder is flared. The liquid digestate (effluent) flows into gravel filters to the holding tanks by gravity and gas pressure. The effluent is UV-treated, after which it is pumped out and reused to dilute incoming faecal sludge, clean equipment, and irrigate the facility gardens. The stabilized sludge is pumped into settling tanks and later dried in open-air sludge drying beds. The dried sludge (biosolids) is physically scraped and stored onsite before being used as a soil conditioner. A soak pit collects the leachate from the drying beds. The solid waste from bar screens is transported to the dumpsite for disposal.

The Integrated Life-Cycle Carbon-Footprint Analysis model was used to assess the FSTP involved 3 phases, as shown in **Figure 2**, i) Descriptive analysis, ii) GHG emissions Analysis and; iii) Performance (efficiency) analysis. Descriptive analysis was the first phase before assessing the plants' emissions to understand the size and complexity (plant capacity). Then an analysis of the plant life cycle emissions was conducted. The plant Operational efficiency analysis was then computed from the established plant capacity and plant life cycle Emissions.

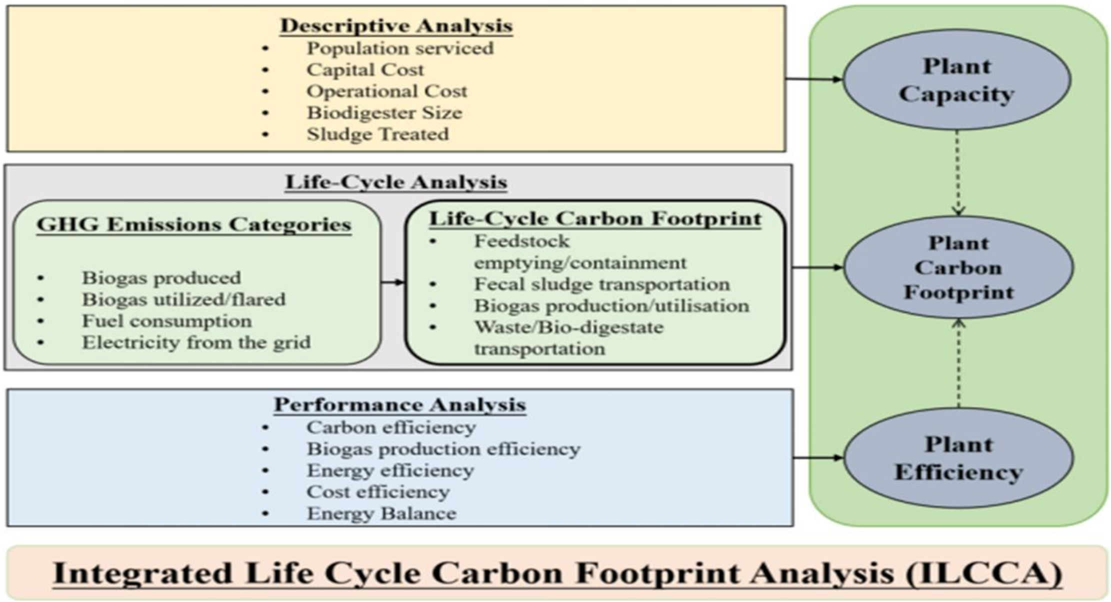


Figure 2: Integrated Life-Cycle Carbon-Footprint Analysis (ILCCA) research framework.

For uniformity and ease of comparison between the two plants, the treatment of $1m^3$ faecal sludge was used as the functional unit in this study. The analysis covered the whole operation life cycle of faecal sludge treatment. The process chain was divided into the following stages.

i. Containment and emptying of feedstock (faecal sludge);

ii. Transportation to the treatment plant;

iii. Treatment process or biogas production;

iv. Final transportation and disposal/reuse of waste/digestate.

Since the plants are around 10 years old in operation, only the operational phase of the FSTPs was considered in the system boundary. The system boundaries also included fuel and energy usage as well as carbon dioxide (CO_2), and other GHG emissions generated during the process such as methane (CH_4) and nitrous oxide (N_2O).

Historical data for the year 2018 on the plants' operations and capacity were collected from each FSTP. The data collected included the size of the biodigesters, the population serviced, and the quantity of faecal sludge they can treat as well as the amount of biogas produced as shown in **Table *1***.

Table 1 Descriptive information about the FSTPs and their operational capacity

Description	**Name of FSTP**		**Units**
	Chazanga	**Kanyama**	
Resident population	200,000	250,000	Persons
Population with pit latrine	90	90	%
Operational cost	12960	17280	USD ($)/year
Biodigester size	50	58	M^3
Capital cost	166,500	70,000	USD ($)
Sludge treated	2293	2548	m^3/year
Biogas produced	4232	4550	m^3/year
Biogas consumed	52	52	%
Biogas flared	48	48	%
Percentage of electricity on operational cost	1	1	%
Vehicle travel distance	7,747	31,814	Km/year
Service Radius	15	25	Km
Electricity from grid	728	970	kWh/year

The GHG emissions from the four stages of the processes from each FSTP were calculated to determine the total carbon footprint of the FSTPs. This was based on the Greenhouse Gas Protocol's calculation tool (GHG-Protocol, 2021). The tool is a free Excel-based calculator for measuring life cycle GHG emissions.

For energy, data such as the source of energy and the quantity consumed in terms of kWh was collected. The quantity of electricity consumption was recorded from the power utility company - Zambia Electricity Supply Company (ZESCO) invoices. For transportation, fuel usage was determined using invoices and register books for vehicle trips of individual vehicles. The data collected included the distances covered by the ferrying trucks, the amount of fuel consumed as well as the type of fuel and vehicle used. Data on the energy inputs and outputs were collected from the monthly averages which did not show significant differences among the months. This was used to calculate yearly totals. This data was put in the GHG Protocol calculation tool (Table 2 and Table 3) and was used to compute the total GHG emissions from these plants based on the IPCC guidelines for country-specific GHG inventory.

In the GHG calculating tool, emissions were calculated using (Equation 1 by multiplying the quantities of units involved with the related emission factors as shown in Table 2 and Table 3. The calculation was based on the Global Warming Potential factors (GWP 100) measured in kilograms of Carbon Dioxide Equivalent ($kgCO_2e$).

$$Emissions_{GHG,\ fuel} = Fuel\ Consumption_{fuel} * Emission\ Factor_{GHG,\ fuel} \qquad (Equation\ 1)$$

Table 2 shows the Emissions from electric power utilization which were calculated using Zambia’s country-specific emission factor of 0.146$kgCO_2e$/kWh established by the International Renewable Energy Agency (IRENA, 2020). Where data was unavailable, default values in the calculating tool were used. For example, in Table 3, when calculating emissions from fuel consumption, an emission factor of 1.47$kgCO_2e$/km established by the EPA (2018) for medium-heavy-duty trucks was used.

Table 2. Calculation of GHG emissions from electric power consumption at each FSTP

User-supplied data					**Emissions tCO_2e**	**Emission Factor $kgCO_2e$/kWh)**
FSTP Name	**Amount of Electricity**	**Units**	**Calculation Approach**	**Type of Emission Factor**		
Chazanga	728	kWh	Purchased Electricity - Market-Based	Grid Average/Location Based	0.11	0.146
Kanyama	970	kWh	Purchased Electricity - Market-Based	Custom emission factor	0.14	

Table 3. Calculation of GHG emissions from transportation of faecal sludge for each FSTP

Name of FSTP	Category	Mode of Transport	Activity Type	Vehicle Type	Amount of Activity Type	Unit	GHG Emissions (tonnes)				Emission Factor ($kgCO_2e$/unit)
							CO_2	CH_4	N_2O	Total CO_2e	
Chazanga	Upstream T&D*	Road	Vehicle Distance	Medium/Heavy-Duty	7747	Vehicle-km	11.36	0.00011	0.000078	11.39	1.47
Kanyama	Upstream T&D*	Road	Vehicle Distance	Medium-Heavy-Duty	31814	vehicle-km	46.67	0.00045	0.00032	46.77	

**T&D is Transportation and Distribution*

The heat energy produced from biogas utilisation for cooking within the premises was also considered in calculating the FSTPs' carbon footprint. This energy was calculated based on the conversion of 2.198 kWh of heat energy and 2.074 kWh of electric energy from 1m^3 biogas (Szabó et al., 2014).

Key estimates were also made to establish the efficiency of the FSTPs from the treatment of 1m^3 of faecal sludge. These were the Operational Cost ($/day), Cost efficiency ($/m^3), Emissions (Environmental) efficiency ($kgCO_2e/m^3$), Energy intensity (kWh/m^3), and Biogas production (m^{3}gas/m^3).

The environmental implications of the FSTPs' construction and demolition were not considered. This is because they were assumed to be negligible due to the length of time (10 years) the plants have been in operation. The reason for this exclusion is that Plants with a longer operational lifetime have a lower percentage of environmental consequences from construction and demolition (Mezzullo et al., 2013). Production of faecal sludge or excreta from humans was excluded from consideration. This is because it was considered a normal biological process which does not involve significant GHG-emitting activities and therefore has no ecological consequences (Poeschl et al., 2012). The application of biosolids for soil conditioning and the burning of biogas at the facilities were not included in the calculation as the Carbon emissions produced from these processes were considered to be biogenic (Vu et al., 2015). Emissions coming from liquid digestate were also ignored. This was because it was reused to dilute incoming FS; therefore, no surplus emissions were produced from it.

The GHG emissions associated with commuting staff responsible for emptying latrines and operating the FSTP were assumed to be low, as concluded by (Szabó et al., 2014). They were therefore not taken into account in the carbon footprint calculation.

III. RESULTS

a. The carbon footprints

The total carbon footprints and breakdowns in each of the four stages in the system boundary to the overall plants' carbon footprint for the two FSTPs in the year 2018 were established and summed up as shown in Figure 3. The percentage contribution of each of these stages is also presented in **Error! Reference source not found.**. Transportation of faecal sludge from households to the treatment plants was the highest emitting stage with Kanyama producing about 44.43 tCO_2e while Chazanga had 10.82 tCO_2e. The total carbon footprint for Kanyama and Chazanga was found to be 46.91 tCO_2e and 11.50 tCO_2e, respectively.

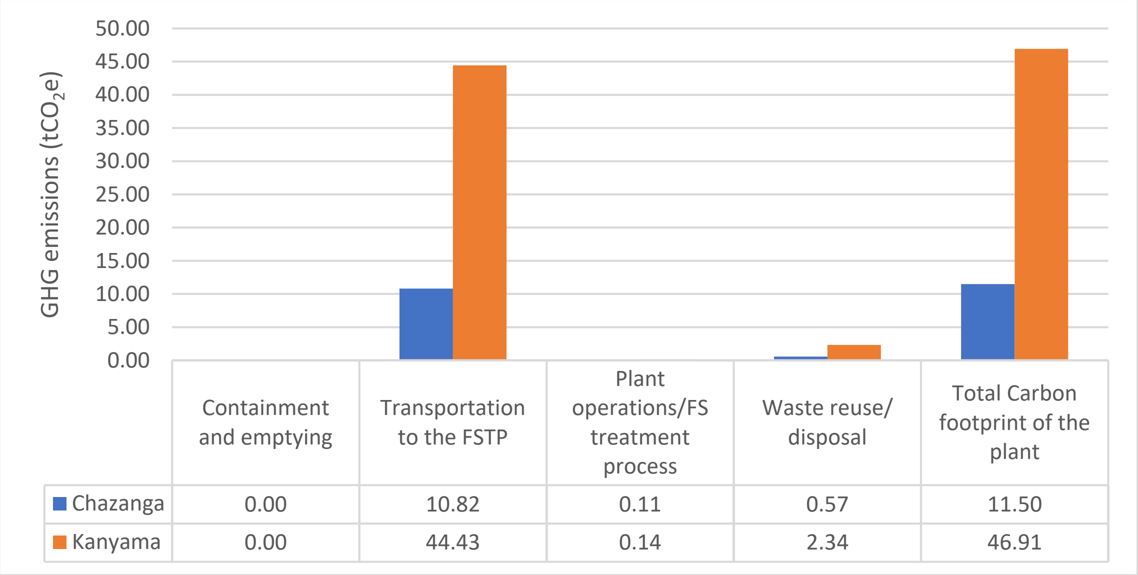
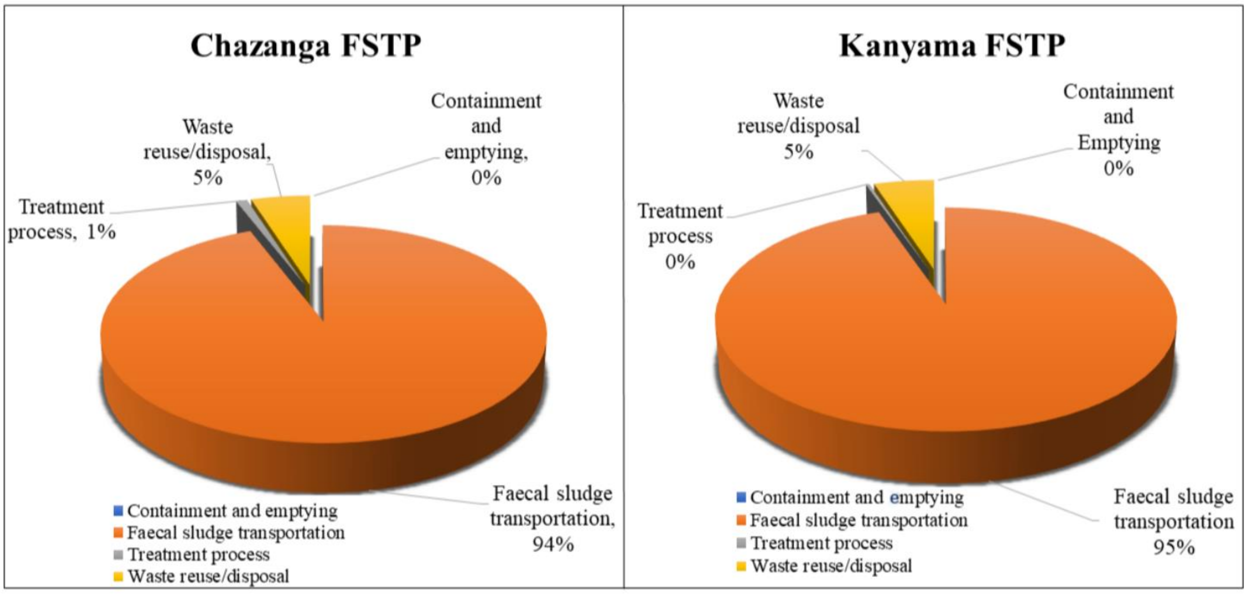


Figure 3. The FSTPs' GHG emissions in different stages of the System boundary contribute to the total carbon footprint



(a) (b)

Figure 4. Contribution of each stage to the total CF for Chazanga (a) and Kanyama (b)

The second largest contributor was the Waste reuse and Disposal stage. The main contributing factor in this stage was the transportation of the solid waste to the dumpsite. The reason for this was that emissions from the biosolids and effluent were not included in the calculation due to reasons stated under MATERIALS AND METHODOLOGY. The GHG emissions from this stage accounted for about 5% of the total emissions in both FSTPs.

The plant operations and treatment stage was the second least GHG emission-contributing stage in both plants. This stage's emissions were primarily determined by their energy needs for site operations. This included mainly electric power for lighting and pumping. The plants utilized 970 kWh/year and 728 kWh/year for Kanyama and Chazanga respectively (see **Table *1***). The plants' operation and treatment stage carbon footprints were 0.14tCO_2e Kanyama and 0.11tCO_2e Chazanga. This accounted for around 1% of the overall carbon footprint of the FSTPs. The Containment and emptying of the FS stage did not have any emissions as it is mostly done manually and no records of fuel consumption were available for the few times it is done mechanically.

b. Operational Efficiency

The operational efficiency parameters of the two plants were calculated as shown in Table 4. These were then compared between the two plants and with other similar studies in other countries. The estimate for the environmental efficiency was computed by dividing the total emissions from each plant in a year (from Figure 3) by the total amount of FS treated (Table *1*) in the same period. It was established that under the Zambian conditions, the treatment of $1m^3$ faecal sludge produces about 18.41 $kgCO_2e$ and 5.02 $kgCO_2e$ emissions of the plants for Kanyama and Chazanga, respectively. The treatment efficiency was estimated by dividing the total biogas produced by the amount of faecal sludge treated in a year. This was estimated to be 1.8 m^3. This means that 1.8 m^3 of biogas was produced from every 1 m^3 treated in these FSTPs.

The energy intensity of the plants was estimated by dividing the energy consumed by the FS treated in the same period. This was found to be 1.03 and 1.23 kWh/m^3 for Chazanga and Kanyama respectively. Similarly, the cost efficiency was calculated by dividing the plants' operational cost by the amount of faecal sludge. The cost of treating the same quantity of faecal sludge was found to be $5.09 for Chazanga and $7.54 for Kanyama.

Table 4 The plant efficiency parameters comparison between the FSTPs and with other countries

Parameter	Unit	FSTP		Other country Averages and literature sources		
		Chazanga	Kanyama	Quantity	Country	Source
Emissions for producing 1 m^3 of biogas	$kgCO_2e/m^3$	2.53	10.31	2.72	Egypt	(Ioannou-Ttofa et al., 2021)
				3.20	Vietnam	(Vu et al., 2015)
				0.24	L. America	(Pérez et al., 2014)
Environmental efficiency	$kgCO_2e/m^3$	5.01	18.41	1.00	Poland	(Wakeel et al., 2016)
				0.28	South Africa	(Wang et al., 2016)
				2.47	Jordan	(Saidan et al., 2019)
				0.27	China	(Wang et al., 2016)
Treatment Efficiency	Biogas/m^3	1.79	1.98			
Energy intensity	kWh/m^3	1.03	1.23	1.06	Netherlands	(Wakeel et al., 2016)
				0.24	South Africa	(Wang et al., 2016)
				1.50	Mexico	(Valek et al., 2017)
				0.38	China	(Yang and Chen, 2021)
Cost efficiency	$/m^3	5.09	7.54	1.50	Indonesia	(SNV and ISF-UTS, 2021)
Carbon footprint	$kgCO_2e$	11,495	46,909	208,173	Hungary	(Szabó et al., 2014)
				1,500,000	Ethiopia	(Gabisa and Gheewala, 2019)
				366.87	China	(Wang et al., 2018)

The total annual energy consumption and production were established for both plants as shown in Table 5. The energy balance was the difference between energy consumed and energy produced. These included energy from electric power from the national grid and thermal energy from biogas used for cooking. The study found this to be -52163 kWh (with an Energy Balance Index of 21.39%) for Chazanga and -36946 kWh (Energy Balance Index of 27.76%) for Kanyama.

Table 5 The Energy Balance of each FSTP

Type of Energy (kWh/year)	Chazanga FSTP (kWh/year)		Kanyama FSTP (kWh/year)	
	Energy consumed	**Energy produced**	**Energy consumed**	**Energy produced**
Electric Power	2359.2	0	3141.8	0
Thermal Energy from Biogas	0	14196	0	14196
Fuels	64000	0	48000	0
Total	66359.2	14196	51141.8	14196
Energy balance	**-52163.2**		**-36945.8**	
Energy balance index	**21.39%**		**27.76%**	

IV. DISCUSSION

a. Carbon footprints

The overall carbon footprints of the two plants were 46.91 tCO_2e and 11.50 tCO_2e for Kanyama and Chazanga respectively. Two primary sources of emissions were identified as fuel and energy. Fuel accounted for 99% of the emissions while energy 1% of the total emissions in both plants. Among the stages of the FSTP life cycle involved in the system boundary, emissions from feedstock transportation were by far the most significant contributor to the total life cycle carbon footprint. This amounted to more than 94% of overall carbon footprints.

The difference in the overall carbon footprint between the two plants was coming mainly from the feedstock transportation. This could be attributed to the longer distances covered by the trucks in Kanyama in a year (31,814km) compared to those of Chazanga (7,747km). Kanyama plant services a much larger area with a larger population of 250,000 than Chazanga with 200,000.

The result of our study shows that if the transportation of faecal sludge to the treatment plant was to be eliminated, there would be a 94% reduction in the emissions from the FS treatment life cycle.

This result also agrees with other studies, such as Ioannou-Ttofa et al. (2021) where it was concluded that feedstock transportation was the highest contributing factor to the total carbon footprint of similar treatment plants. However, the result is inconsistent with the findings of Szabó et al. (2014) where the production of raw materials was the highest GHG-producing stage. In addition, our results are higher than the findings of the study by Hou et al. (2017), who found that biogas leakages were the major contributing factor to the total GHG emissions of biogas systems in rural China. Our result is also smaller when compared to the study conducted in Egypt by Ioannou-Ttofa et al. (2021), which found 58.81tCO_2e as the plant Carbon footprint where the biodigester size was much smaller with 4m^3 volume. In Egypt, this was attributed to the longer distances covered with the furthest being 90 km whereas the furthest distances covered in our study were about 25 km.

b. Operational efficiency

For environmental efficiency, this study showed that under Zambian conditions, treating 1m^3 faecal sludge produced about 18.41 $kgCO_2e$ and 5.01 $kgCO_2e$ of emissions for Kanyama and Chazanga, respectively. This also translates to carbon emissions of 2.53 $kgCO_2e$ (Chazanga) and 10.31 $kgCO_2e$ (Kanyama) to produce 1m^3 biogas. The result for Chazanga was within the range of the results from studies by Vu et al. (2015) and Ioannou-Ttofa et al. (2021), which found 2.72 CO_2e and 3.2 $kgCO_2e$, respectively as the carbon footprint of producing 1m^3 of biogas. However, both results from this study were significantly higher when compared to similar studies conducted by Pérez et al. (2014) and Zhang et al. (2013), who found 0.24 $kgCO_2e$ and 0.68 $kgCO_2e$, respectively. The Kanyama FSTP's result (10.31 CO_2e) is more than 10 times the results from previous studies - indicating a very poor environmental efficiency, most of which difference is attributed to the longer distances covered by the trucks ferrying FS. This negates the gains made by the technology at the treatment plants in capturing GHG from the faecal sludge collected from pit latrines.

The average energy intensity of 1.13 kWh per cubic meter of faecal sludge treated found in this study is higher than the 0.24 kWh/m^3 for South Africa (Wakeel et al., 2016) and 0.38 kWh/m^3 for China (Yang and Chen, 2021). However, our result is close to the results of other previous studies in the Netherlands, Mexico and Japan with a range of 1.06 ~ 1.89 kWh/m^3 (Mizuta and Shimada, 2010) which were considered to be high. Therefore, the study agrees with the conclusion made by Li and Lu (2022) that most current plants that treat wastewater are energy-intensive.

The cost of treating the 1m^3 of faecal sludge for Chazanga was found to be \$5.09 while for Kanyama it was slightly higher at \$7.54. These values are significantly higher compared to the cost of treating the same quantity of faecal sludges in other similar developing countries, such as Indonesia at $1.50 (SNV and ISF-UTS, 2021). The difference in the cost between the two plants in the current study could be attributed to the difference in the annual operational costs where Chazanga had US$12,960/year compared to Kanyama with US$17,280/year. The highest cost went towards wages and transportation with around 59% and 40% respectively. This is contrary to the findings of the study by Hernández-Sancho and Sala-Garrido (2009) where maintenance and waste management costs were the main factors affecting the cost efficiency of wastewater treatment plants.

As shown in Table *5*, it was found that for both plants, the energy balance was far from neutral, let alone positive. There was more energy consumed than produced, and thus the energy balance was negative in both plants, i.e. -52,163 kWh/year for Chazanga and -36,946 kWh/year for Kanyama. These results were not consistent with those found in a study of a biogas plant utilizing crops as feedstock by Szabó et al. (2014). Szabó et al. (2014) found the energy balance to be positive at 6,235,000 kWh/year. These results were also at variance with the suggestions of the SDG 6 Synthesis Report on Water and Sanitation (Water, 2018) that the amount of energy that is contained in wastewater is approximately 5–10 times what is required to treat it. This could be attributed to the Zambian plants' non-utilization of the biogas produced and the high fuel consumption for transportation of feedstock due to the large areas covered.

c. Policy Implications

For developing countries, especially in sub-Saharan Africa, which are still grappling with providing sustainable sanitation to their populations and meeting SDG 6 of halving the amount of untreated wastewater by 2030, the result of this study can provide basic information needed to design better FSTP systems and avoid unnecessary waste in resources, energies and costs. For Zambia, this will act as a guide in providing sustainable faecal sludge management with resource recovery and reducing GHG emissions as envisaged in The Zambia Nationally Determined Contributions by 25% by 2030 from the 2010 levels (ZNDC, 2021) and the national policy for urban sanitation (NUSS, 2015).

The integrated approach of this study gives a clearer understanding of not just how much resources are consumed in a life cycle but per unit of raw materials treated or biogas produced. This helps in determining the viability of the given system or technology. Including operational efficiency in the ordinary LCA model will make it easy to compare these results with different technologies and localities. This study provides context and a reasonable estimate of the system's environmental sustainability, given its operational efficiencies.

The findings of this study may serve as a basis for finding ways to reduce emissions from the identified hotspots, improve existing systems as well as establish new ones. The information could also be beneficial for estimating the GHG emissions of an FSTP using a biogas system under similar conditions. It could also be utilized to decide what type of faecal sludge treatment system to be built based on certain parameters like feedstock and biodigester size. Therefore, the use of models and tools allows managers to identify the strengths and weaknesses of FSTPs and consequently make adjustments to reduce not only emissions and improve performance but also reduce costs.

d. Uncertainty and limitations

The assumptions taken in determining the research scope and selecting the system boundary may have resulted in uncertainties in this study. For instance, biodigesters were also assumed to be airtight, implying that there were no leaks from the digesters. The study concentrated on the emissions and efficiency associated with the operation processes only, excluding the manufacturing of building materials and construction of the latrines and FSTPs.

The major limitation was the non-availability of data specific to Zambia in determining some parameters to measure GHGs. For example, country-specific conversion coefficients for Zambia for fuel consumption were not readily available. There was also no data on the influent and effluent BOD to calculate the plants' treatment efficiency accurately. These limitations could have led to slightly higher or lower predictions as some indicators could not be established.

e. Recommendations

To reduce emissions and increase the overall environmental footprint for the existing and future plants, policymakers and decision-makers should consider developing incentives to encourage the building and installation of new and adequately sized FSTPs in all peri-urban residential areas. This will reduce the long distances travelled in the transportation of faecal sludge. It is also recommended that technologies such as Combined Heat and Power (CHP) be used to produce electricity from the biogas that could have otherwise been flared or released into the atmosphere.

In future research, the validity of the FSTPs' Carbon footprint should be improved by giving solid data on direct emissions, such as Faecal Sludge containment in pit latrines, leakage from biodigesters, pressure-relief valves, and biogas flaring. These emissions may have an impact on the FSTPs' overall carbon footprint. The influent and effluent characteristics, such as Biological Oxygen Demand, would be interesting to measure for the certainty of treatment efficiency of the technology.

V. CONCLUSION

This study investigated the life cycle carbon footprint of FSTPs as well as their operational efficiency by developing an ILCCA model. The life cycle carbon footprint of the two FSTPs in Zambia was established. It was also found that using this technology under the Zambian environmental conditions, treating $1m^3$ of Faecal Sludge (excrement) produces about $1.8m^3$ of biogas. It was found that the carbon footprint of treating $1m^3$ FS for the two plants was 5.01 $kgCO_2$ equivalents $(CO_2e)/m^3$ and 18.41 $kgCO_2e/m^3$, respectively. FS transportation from households to the treatment plant was the highest GHG emitting process in both treatment plants, accounting for over 94% of the total emissions. This could negate the benefits of using this technology to capture GHGs from FS in latrines.

However, the study also shows that eliminating or improving efficiency in the transportation of faecal sludge or placing the treatment plants as close to households as possibly safe could increase the environmental efficiency of the FSTPs by about 94% The result further shows that the treatment process had the lowest carbon footprint as it captures GHG by producing biogas; indicating and confirming the positive role of using anaerobic digestion technology in waste treatment and recycling. The energy balance of both plants was negative, with an energy self-sufficient ratio of 21.39% and 27.76%, respectively. This implied that the FSTPs consume more energy than they produce.

Having quantified the Carbon footprint and the flashpoints for emissions of the faecal sludge treatment plants in Zambia, it is important to devise certain mechanisms for proper utilization of the biogas energy and optimization of the transport distances to improve the life cycle carbon performance of the plants.

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