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TITLE: ANAEROBIC CO-DIGESTION OF FECAL SLUDGE AND CABBAGE WASTE FOR BIOGAS PRODUCTION

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DECLARATION

I, NABAGGALA MARTHA, swear that the material included herein is entirely original aside from the places where sources have been used and referenced.

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DEDICATION

Thank you to my parents, Mr. Lawrence Mayambala and Mrs. Sarah Mayambala, for their advice and words of wisdom that have helped me go this far.

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LIST OF ACRYNOMYMS

Cd	Cadmium
COD	Chemical Oxygen Demand
Cu	Copper
CW	Cabbage Waste
FS	Fecal Sludge
FSC	Fecal Sludge Cake
K	Phosphorus
Pb.	Lead
SDG	Sustainable Development Goals
TAD	Thermophilic Anaerobic Digestion
Staph	Staphylococcus aureus
OC	Organic Carbon

ABSTRACT

In Sub-Saharan African urban settings, organic waste management and improper disposal of fecal sludge pose critical threats to human health and environmental well-being. Both challenges demand urgent attention and tailored solutions to mitigate their adverse impacts. This research focuses assessing the efficiency of the Thermophilic Anaerobic Digestion (TAD) process for treating FS, co-digesting it with Cabbage Waste (CW) to produce biogas for energy and nutrient-rich bio-slurry for crop cultivation at the same time.

20-liter laboratory batch reactors made of stainless steel for the inner and mild steel for the outer layer with suitable arrangements for feeding, gas collection, and draining of residues were used at a working volume of 18 liters to investigate four substrate ratios: 50F:50C, 75F:25C, 25F:75C, and 100F (FS and CW). A 35-day experiment was done and pH, nutrients (N, P, K, OC), heavy metals, gas composition and volume of gas were all examined. The results showed pH values ranging from mildly acidic to alkaline (6.02 to 8.05), and various nutrient compositions in the mixtures.

Biogas composition analysis showed methane levels between 6% and 69.3%, while carbon dioxide levels ranged from 11% to 62.8%. The 75F:25C mixture yielded the highest biogas volume with values greater than or equal to 1 l/day and methane percentage. The respective methane percentages for Weeks 1 through 5 were 21.1%, 61.1%, 57.2%, 62.8%, and 55.3%. The study also highlighted the potential of using digestate as organic fertilizer due to low concentrations of heavy metals (Pb and Cu).

Key words: thermophilic anaerobic digestion, Fecal sludge, Cabbage waste, Physiochemical properties, Nutrients, Pathogens, Heavy metals.

1 INTRODUCTION

1.1 Background

Many cities in Sub-Saharan Africa lack proper management measures for the voluminous amounts of waste generated daily, posing a threat to human and animal well-being. It is estimated that about 1.6 million tons of organic waste are generated daily in Urban areas (Kaza *et al*.,2018). Among these is Fecal sludge (FS), which is one of the most dangerous organic wastes. Sludge contains large amounts of pathogens and heavy metals, therefore, its poor disposal can result in environmental degradation and an outbreak of deadly diseases such as cholera (Shukla *et al*., 2022). In Uganda, an increasing population growth rate in urban areas has led to a decline in sanitation facilities (McConville *et al*., 2020). Because the sewer network is not widespread (GIZ, 2017), the majority of the population is served by onsite sanitation facilities. These facilities require emptying after certain periods and safe end disposal. (Maqbool, Shahid, et al. 2022). The most predominately used onsite sanitation facilities in Uganda are pit latrines (Semiyaga *et al*., 2022). Emptying service companies are then expected to extract and transfer the FS from the pit latrines to the already set up treatment plants in the country. However, the emptying service charges are too high, and inaccessible in some areas of the country(Kwiringira *et al*., 2016). The people often end up disposing of the FS in nearby water channels during rain events or using it as a fertilizer in their farms, leading to the release of GHG (Nsiah-Gyambibi et al., 2021). FS is rich in plant nutrients and can be used as a substitute for inorganic fertilizer. However, it needs proper treatment to mitigate its harmful environmental effects before it can be used.(Shukla et al., 2022).

Sustainable Development Goal number 6 of the United Nations is geared towards improved water, sanitation, and treatment of wastewater (UN General Assembly, 2015). To fulfill Sustainable Development Goal 6, many countries in Sub- Saharan Africa are devising ways of properly managing the large amount of FS generated by their people (Simiyu, Chumo, & Mberu, 2021). Anaerobic Digestion (AD) is a method of FS treatment that is commonly used. Anaerobic digestion is a biological process that allows for decomposition of organic matter with the help of bacteria, reduction of pathogenic organisms (Ma, Chen, & Ndegwa, 2022) as well as production of methane, a renewable fuel (Burka, Basamykina, & Kharlamova, 2021; Liew et al., 2022). This method doesn’t only stabilize FS, but as well as produces biogas, needed to fulfill the high energy demand(Semiyaga *et al*., 2022). Despite the various research

that has been done about AD, there's limited information about the best combination of solid matter and FS for optimization of the process for biogas production as well as information on the ability of the process to reduce heavy metal content and inactivate pathogens.

1.2 Problem statement

Over 80% of people living in Sub-Saharan Africa use onsite sanitation systems, largely pit latrines and sewer systems(Semiyaga *et al*., 2022). On the other hand, the available FS conventional treatment plants are expensive and not enough to handle the large volumes of FS produced daily in most Sub- Saharan countries, such as Uganda (McConville *et al*., 2019). This has forced many people in slum areas around Kampala to poorly dispose of FS into the environment (McConville *et al*., 2019). However, the FS contains heavy metals and pathogens that threaten human and environmental health (Nsiah-Gyambibi *et al*., 2022).

It is also important to note a large proportion of Uganda's population is dependent on wood fuel (Bamwesigye *et al*., 2020; Jagger & Kittner, 2017) leading to deforestation, hence environmental degradation. Approximately 95% of people in slum areas of Kampala are faced with energy shortages as they are unable to afford the high energy prices for electricity and cooking fuel. (Kizito *et al*., 2022; Lubwama & Yiga, 2018). This project proposes the use of Anaerobic Digestion to offset the high energy needs (Semiyaga *et al*., 2022) as well as stabilize FS through the reduction of disease-causing pathogens such as E-coli.

In Uganda optimization of Anaerobic digestion has been studied using Chicken manure as the substrate and biochar as a co-substrate ("Synergetic effects of biochar addition on mesophilic and high total solids anaerobic digestion of chicken manure," 2022b) but little focus on utilizing FS as a substrate.

This study is therefore aimed at observing the process of Anaerobic Digestion of FS, using cabbage waste (CW) as co-substrate as well as investigating the potential usage of the bio-slurry as a crop fertilizer.

1.3 Main objective

To assess the efficiency of Thermophilic Anaerobic Co-digestion (TAD) of FS with cabbage waste for energy and crop production.

1.4 Specific objectives

i. To characterize Fecal Sludge Cake (FSC) and Cabbage waste (CW) for AD.

ii. To determine the combination of substrates with optimal biogas production.

iii. To characterize digestate and analyze nutrients for their suitability for crop growth.

1.5 Research Question.

i. What is the best mixture of FSC and CW for biogas production?

1.6 Justification

This study is essential since the FS management facilities that are currently in use cannot handle Uganda's whole production of FS. Farmers purchase the dewatered FS from the nearby treatment facilities, however, because it contains pathogens, it is a risk to the food chain when applied directly on soils without further treatment. Innovative FS management solutions would be put into use to address the problem of negligent FS disposal from on-site systems into the environment. Health and the environment will both benefit from this. As awareness of the potential problems associated with FS management became clear, this research would ensure that more effort is devoted to small scale treatment of FS at the home level the act of discharging unexpurgated feces into the environment. Another energy source that can be used in treatment facilities in place of the pricy electricity is provided by this treatment.

1.7 Workflow chat

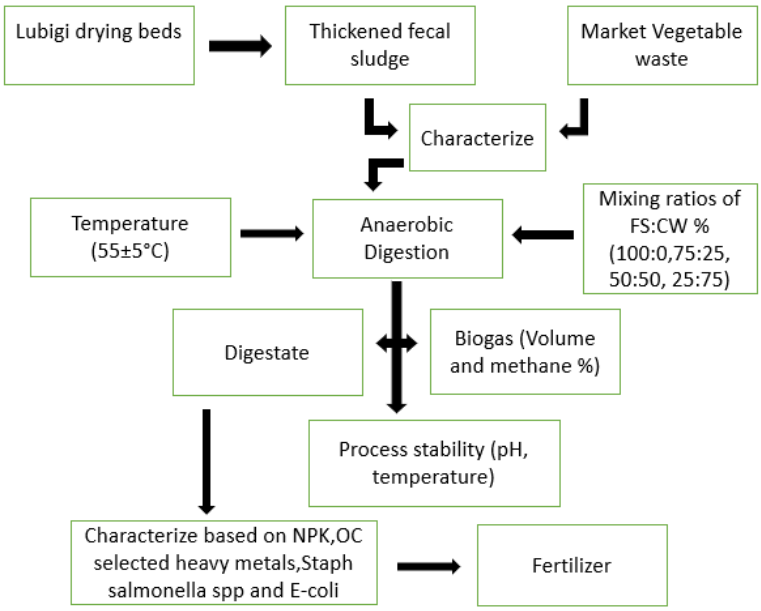

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Figure 1:Workflow chart

2 LITERATURE REVIEW

This chapter explains FS, its treatment, and different approaches.

2.1 Fecal Sludge

FS mixture of human excreta, water, and solid waste that accumulates in onsite sanitation technologies and specifically not what is transported through the sewer system. It is composed of urine, feces and anything else that goes into the onsite containment technology, such as grey water, cleansing material and menstrual hygiene products (Velkushanova et al., 2021).Thus FS varies according to quantities and qualities depending on what people use and what they feed on. FS is both a hazard (contains pathogens, heavy metals, and other contaminants) and a resource (contains nutrients).

2.2 FS characterization

FS composition and traits vary greatly from person to person and from location to location. The contents of the same pit are not homogeneous either. Table 1 is a summarized characterization of sludge (Rweyemamu, 2014) with comparison between public toilet and septage to better understand the difference in characteristics.

Table 1: Fecal sludge characterization

Parameter	Faecal and WWTP sludge characteristics (mean and range values)	
Characterization	Public toilet or bucket latrine	Septage
	Highly concentrated, mostly fresh, stored for days or weeks only	FS of low Concentration usually stored for several years
Total Solids (mg/L)	52,500	12,000 - 35,000
	30,000	22,000
	≥ 3.5 %	< 3 %
Total Volatile Solids (% TS)	68	50-70
	65	45
COD (mg/L)	49,000	1,200 - 7,800
	30,000	10,000
	20,000 - 50,000	<10,000
BOD5	7600	840 - 2,600
BOD:COD	0.16	0.7 - 0.33
Total Nitrogen (TN) (mg/L)		190 - 300
Total Kedjal Nitrogen (TKN) (m	3,400	1,000
NH4-N	3,300	150 - 1,200
	2,000	400
	2,000 - 5,000	<1,000
Total Phosphorus (mg/L)	450	150
Faecal Coliforms (CFU/100 mL)	1.00E+05	1.00E+05
Helm. Eggs /L	25 000	4 000- 5 700
	20,000 - 60,000	4,000
	20,000 - 60,000	4,000
		600 - 6,000

Source: (Rweyemamu, 2014)

2.3 Fecal Sludge Management (FSM) in Uganda

In FSM, the FS is stored in onsite technologies such as septic tanks, collected and transported by cesspool trucks to the treatment plants and disposed or used safely. The major key player in Uganda in FS management is National Water and Sewerage Co-operation (NWSC). It operates and maintains wastewater treatment plants such as Lubigi plant that receive both sewerage and FS from emptied septic tanks and pits. It also operates vacuum tankers in a few towns to provide septic tank and pit emptying services (Nuwagira, 2021).

2.4 Collection and transportation

Sludge from semi-on-site sanitation systems is collected to start the FS cycle, which can be manually or mechanically conducted. The most common method of FS collection is use of manual labor since it is inexpensive and time-consuming. It involves access to the sanitary

system, frequently with the person within the pit and using spades and buckets. There is rather development of equipment that will let the worker collect sludge manually.

The mechanical collecting method is thus more effective to swiftly remove bigger amounts of sludge with little direct contact, hence lowering health concerns. This innovation is typically pricey and vulnerable to mechanical failure (Velkushanova et al., 2021).

2.5 Lubigi wastewater treatment plant

Lubigi sewage treatment plant in Kampala, Uganda, has a capacity of 5,400 m^3/day and a current flow of 3,000 m^3/day and treats domestic wastewater and FS from pit latrines and septic tanks. FS has a treatment line as shown in Figure 2 and the treatment plant has 19 drying beds for FS. Each bed is 7x34 meters in size and treats about 71,000 liters of sludge at a time. Because the wastewater and FS are treated separately in the treatment plant, the drying beds only contain pure FS (Englund & Strande, 2019).

Trucks transport the sludge that enters the treatment plant, which is primarily from pit latrines and septic tanks in homes and other buildings (Lindberg & Rost, 2018).

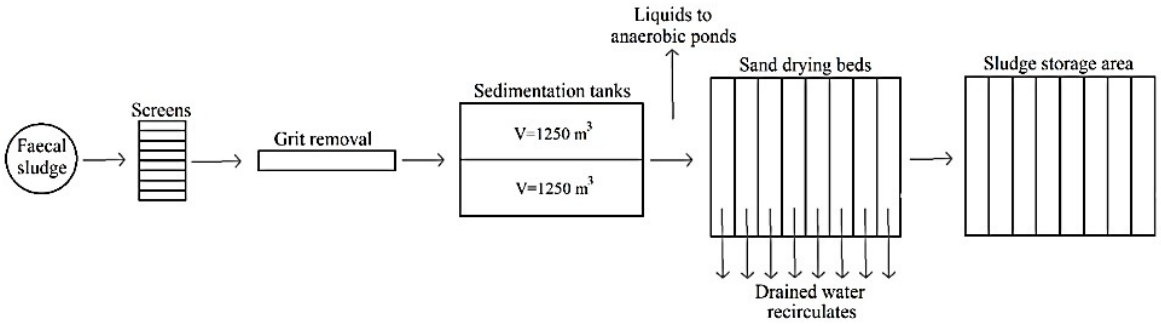


Figure 2: The FS treatment line at Lubigi sewage treatment plant in Kampala, Uganda

Source: Lindberg & Rost, 2018

2.5.1 Primary treatment

This is the first stage that the delivered FS undergoes. It involves screening and grit removal chambers. Screening is a physical treatment that separates municipal solid waste and large solids from influent water. For a variety of reasons, including a lack of other solid waste management systems, municipal solid waste ends up in pit latrines. Clogging and pump failures are avoided by removing solids. Bar screens function as a barrier for incoming flow, trapping solids while allowing liquid and smaller particles to pass through. The efficiency of the screens is affected by the gap between the bars and the incoming flow velocity; the

smaller the gap and the lower the velocity, the higher the efficiency (Bassan, 2014; Lindberg & Rost, 2018).

Sand and grit are removed from the FS to prevent damage to the pipes and pumps in the treatment line. Grit and sand are allowed to settle in a channel because they are too tiny to be removed by bar screens. Removal effectiveness is influenced by both flow velocity and channel length (Bassan, 2014; Strande & Brdjanovic, 2014).

2.5.2 Secondary treatment

The sedimentation tank acts as a secondary treatment but can only hold the FS for a maximum of three months. The tank is filled with sludge for the first month. The sludge in the tank is continually pumped to the drying beds for additional treatment during the second month.

The tank is simultaneously being refilled with fresh incoming sludge. The third month is spent letting the sludge settle in the filled sedimentation tank. Three days pass after the liquid portion of the FS is removed from the solid portion using gravitational forces and sent to anaerobic ponds (Figure 3) where it is co-treated with the wastewater (Lindberg & Rost, 2018; Nuwagira, 2021).

Figure 3: Stabilization ponds

Source: Nuwagira, 2021.

2.5.3 Drying beds

The sand drying beds are filled with the settled sludge. The wastewater treatment line receives the water that has been drained from the drying beds that are packed with FS for co-treatment (Nuwagira, 2021). Since the roofs covering the beds are leaking, the amount of time it takes for the sludge to dry in the beds varies depending on the quantity of precipitation and the state of the roof. The sludge is kept in storage for an added six months after drying. The sludge is sold and transferred to farmers to be utilized as a soil supplement after a total treatment time of roughly 11 months (Lindberg & Rost, 2018).

2.6 Treatment technologies of FS

Treatment technologies are classified based on the level of adoption, research, innovation, and expert knowledge that is required for successful implementation. Therefore, this section is focusing on some of the established technologies whose design and their operational and maintenance guidelines can be readily recommended.

2.6.1 Settling-thickening tanks

The major aim of settling-thickening tanks (Figure 5) is separation of the liquid and solid fractions of FS (Figure 4). This implies that pathogen inactivation does not occur, and both liquid effluent and settled sludge require further treatment. The major fundamental mechanisms are settling, thickening and flotation.

The thickened sludge is in most cases removed after 5 to 30 days using pumps, front-loaders and manually with shovels. The method of removal is dependent on the thickness of the sludge.

The tanks are rectangular in shape and FS is discharged into the inlet and supernatant exists through the outlet at the opposite side, the solids are therefore kept at the bottom. The scum such as fats, oils and grease, float to the top of the tank.

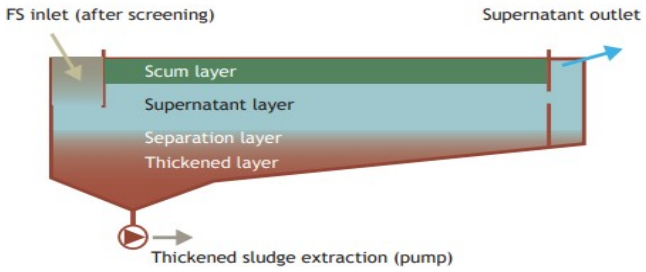


Figure 4: Settling-thickening tank illustration.

Settling-thickening tanks (Figure 5) can be used in any climate but are preferable during treatment of FS with a relatively low solids concentration and in areas with rainy climate.

Figure 5: Settling-thickening tanks.

2.6.2 Unplanted drying beds

The major aim of unplanted drying beds (Figure 7) is dewatering as well as drying of FS but little focus on pathogen activation. The leachate requires further treatment because of its higher nutrient and organic content compared to a usual wastewater treatment influent. The dewatered and dried solids may also be treated further depending on the end use. They are designed based on solids and hydraulic loading rates and are batch operated.

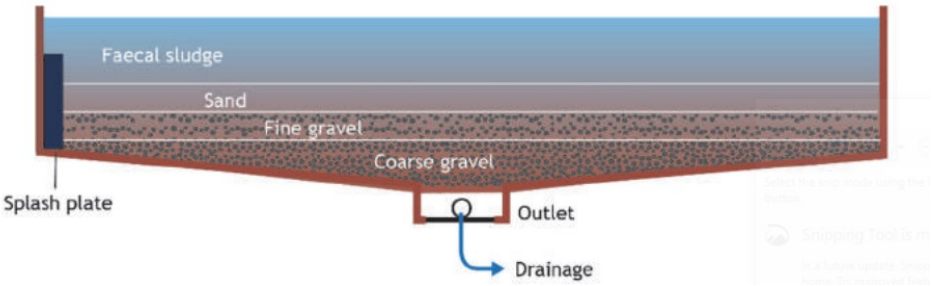


Figure 6: Unplanted drying beds illustration

If the removal of FS is done using a wheelbarrow and shovel, a ramp should be included in the design above the sand. Like the sludge-thickening tanks they are also rectangular with a splash plate that disrupts flow during loading as shown in Figure 6. The filter medium is made up of sand and gravel layers increasing in diameter downwards.

Figure 7: Unplanted drying beds

2.6.3 Planted drying beds

Planted drying beds are similar to unplanted drying beds in terms of the major aim but they stabilize FS instead of drying it. They are also designed based on hydraulic and solids loading rates. In the planting beds, the filter bed is used for growing plants, and it is fed continuously with FS (Figure 8). The beds are loaded 1-3 times a week with a hydraulic loading rate of 7.20cm of sludge per loading depending on the context (Englund & Strande, 2019).

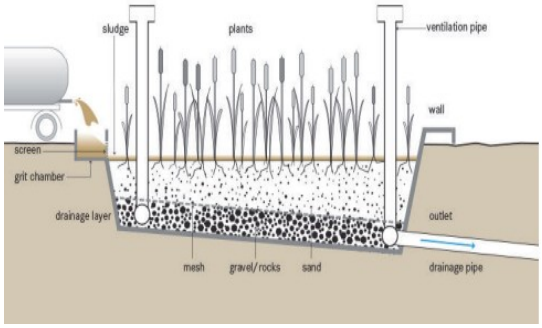


Figure 8: Planted drying beds

The ventilation pipes are installed to insure constant air flow through the media, the plant roots and stems. The plants help in the dewatering and the stabilization of organic matter and inorganic matter in FS as well as prevent the bed from blockage. Plant species are selected based on their ability to adopt to the hostile FS conditions as well as the resource recovery objectives (Strande & Brdjanovic, 2014).

2.6.4 Co-composting

Composting is the biological degradation process of heterogeneous solid organic materials under controlled moist, self-heating, and aerobic conditions to obtain a stable material that can be used as organic fertilizer (Lobo & Dorta, 2019).

The product of composting is composite which is stable, requires no further treatment and can be used as a soil additive to improve soil structure and supply nutrients. It is advisable to co-compost (Figure 9) FS with another carbon-rich organic substance because of its low carbon to nitrogen ratio and high liquid content. This allows for attainment of a C/N between 20:1 and 35:1 and if the co-composting process properly operated, treatment goals such as pathogen reduction, nutrition management, and stabilization can all be achieved.

The pathogen inactivation is usually achieved by using thermophilic conditions over a given period of time.

Sludge usually dehydrates to 30-50% and C:N ratio 18.22 ± 11.12. For example, in Ghana, the FS that IWMI treats is 93-99% water, and after bed dehydration, the dry FS has C:N ratio is 11±3 (Cofie, 2016).

The three organic composting technologies are: 1) windrow; 2) aerated static; and 3) in-vessel. Solid waste such as plastic does not decompose and must be treated before co-composting.

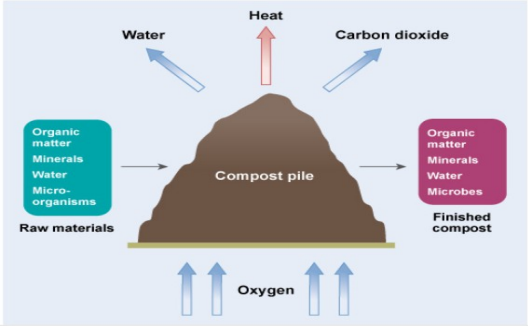


Figure 9: Co-composting illustration

Source: Open Learn Create

2.7 Innovation technologies of FS

These are technologies that are promising and potentially ready to be scaled up but are currently still at the plot scale of development. These include AD, Conditioning, Solid fuels from FS, Vermi and fly larvae treatment and Lime stabilization and ammonia treatment. In this section the focus is directed towards AD.

2.7.1 Anaerobic digestion (AD)

AD is a viable and cost-effective method to convert organic waste into usable renewable energy (Hoang et al., 2022). It can also be defined as a biochemical process during which complex organic matter is decomposed in absence of oxygen, by various types of anaerobic microorganisms (Adekunle & Okolie, 2015). Biogas, the product is clean and renewable.

Currently, anaerobic digestion is getting more and more attention, both as a solution to environmental problems and as a as a source of energy for today's energy-intensive lifestyle (Asam et al., 2011).

2.7.2 Stages for biogas production

Anaerobic digestion is generally considered a multipart process, the decomposition itself being based on the reduction process that includes a number of biochemical reactions that take place under anoxic conditions.

Methane formation in anaerobic digestion consists of four different steps (Figure 10): hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The rate limiting step for complex organic substrates is the hydrolysis step due to the formation of toxic by-products (complex heterocyclic compounds) or undesirable volatile fatty acids (VFAs) formed during hydrolysis step while the methanogen process is the rate limiting step for biodegradable substrates.

The microorganisms that carry out the decomposition reactions in each of these stages are very different from each other physiological, nutritional requirements, growth kinetics and environmental sensitivities (Kovács et al., 2013). These microorganisms can generally be characterized as acid forming and methane forming.

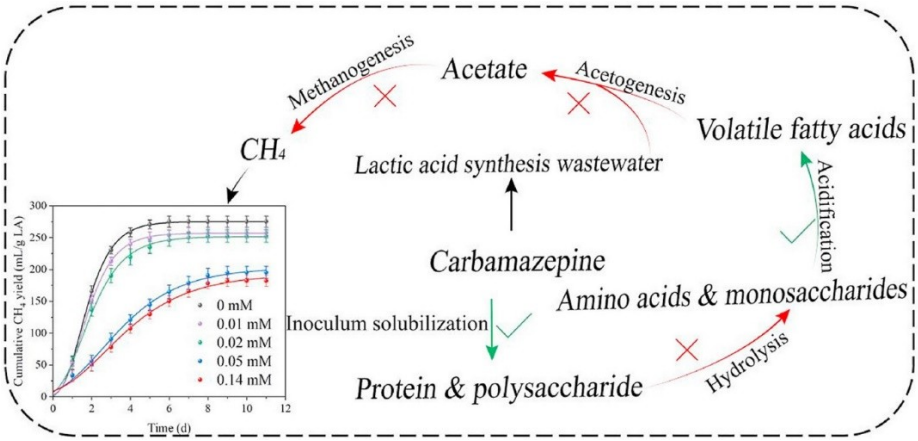


Figure 10: Biogas production stages

Adopted from (Cofie, 2016)

2.7.3 Operation parameters for large or medium size biogas digesters.

Total Solids (TS)

TS is a term used to describe the dry matter in a sludge, regardless of whether it is organic or inorganic. It is frequently expressed in the literature as either a percentage or a concentration. By repeatedly drying a sludge sample at 103-105 °C until no further weight change is visible, the TS concentration is ascertained.

In addition to being an assessment of the influent, TS is a critical component of digester performance. Because it requires smaller digester capacity and less heating, high-TS anaerobic digestion has attracted a lot of attention recently(Yi et al., 2014). Additionally, continuous high-TS digesters showed higher biogas outputs than low-TS digesters running at the same retention duration (Duan et al., 2012).

Biochemical Oxygen Demand (BOD)

An indicator of the amount of biodegradable organics in sludge is the biochemical oxygen demand (BOD), which can also be used to gauge how well an anaerobic digester is working overall. BOD measures the dissolved oxygen microbial metabolism in a particular sludge sample over a five-day period. In the end, BOD is a measurement that may be used to estimate the concentration of biodegradable organics present in sludge by measuring the amount of dissolved oxygen required to support aerobic microorganisms in a sludge sample over an experimental period of five days (Zupančič & Grilc, 2012).

Chemical oxygen demand (COD)

A measure of the amount of oxygen in a sample of sludge that can be consumed in a reaction with oxidizing agents is provided by chemical oxygen demand (COD). The amount of organics in a sludge is commonly represented as COD in anaerobic digestion. COD decrease can indicate the degree of degradation occurring inside an anaerobic digester as it indicates the consumption of organics, and it can be used to assess the effectiveness of anaerobic digestion. It's logical that COD has a greater value than BOD because it measures all of the organic materials in a sludge. Therefore, the biodegradable portion of a sludge can be represented by the ratio of BOD to COD (Zupančič & Grilc, 2012).

Loading rate

The volume of organics given to a digester each day is referred to as the loading rate of a digester in continuous digesters. Due to the waste being hydrolyzed and acidified more quickly when a digester is overloaded, this might cause issues. This can result in an excessive buildup of acid and disrupt the anaerobic digestion process by possibly preventing methanogenesis (Franke-Whittle et al., 2014).

Studies on overloaded grease waste digesters showed that rapid shocks in the loading rate could cause shifts in microbial populations, and the methane yields reverted to normal levels after developing a tolerance to increased loading rates (Ferguson, Coulon, & Villa, 2016). Following an initial overloading event, the digester performance and resilience to overloading are believed to have improved due to the increased diversity of methanogenic bacteria.

Hydraulic Retention Time (HRT)

A shorter HRT is correlated with a higher loading rate as a loading rate-related metric. Shorter HRTs are therefore known to be linked to VFA acidification, which may have inhibitory effects (Kim et al., 2013). Generally, mesophilic digestion can be accomplished within 15–30 days (Mao et al., 2015).

Temperature

Mesophilic (35°C) and thermophilic (55°C) temperature regimes are the two primary anaerobic digestion temperature ranges. However, mesophilic digesters continue to be appealing due to their reduced heating energy costs compared to thermophilic digesters (Moset et al., 2015). Mesophilic digestion occurs at a lower temperature, therefore digestion at this temperature regime is slower and yields less biogas.

On the other hand, thermophilic digestion works at a greater temperature. As a result, response rates rise, potentially resulting in larger loading rates as well as enhanced methane output (Hartmann & Ahring, 2006). Additionally, it is known that thermophilic digestion destroys pathogens at higher rates, which may be advantageous in jurisdictions where there are restrictions on the presence of pathogens in effluents (Smith et al., 2005).

C/N ratio

A typical way to characterize nutrients is by looking at a substrate's carbon/nitrogen ratio (C/N ratio). Protein decomposition stands to reason as the most common supply of nitrogen in an anaerobic digester given the composition of proteins, lipids, and carbs. A certain quantity of nitrogen is also required to prevent the protein production of bacteria from being affected, just as a certain concentration of carbon is required to give a sufficient substrate for digestion (Zupančič & Grilc, 2012).

As co-digestion of various substrates has been used more frequently, the C/N ratio has also received attention. In a more recent experiment, mesophilic and thermophilic digesters were used to co-digest dairy manure, chicken manure, and rice straw. At C/N ratios of 25:1 for mesophilic digesters and 35:1 for thermophilic digesters, an ideal methane potential and reduced ammonia inhibition were found (Wang et al., 2014).

AD with FS

AD with FS's primary treatment goal is stabilization, which is accomplished by a microbiological process in which organic waste is broken down in the absence of oxygen. There are three categories of anaerobic digestion systems for FS: low, medium or high complexity depending on their size, the level of centralization, the necessary management level, and the operational abilities (Englund & Strande, 2019).

The digesters often found at large centralized wastewater treatment plants for the treatment of activated wastewater sludge are examples of high-complexity anaerobic digestion systems. High management and operational abilities are needed. For the treatment of FS, these digesters have not yet been widely utilized. The rural, household-level, modest, passive systems that primarily utilize manure and food waste with some co-treatments of FS are known as low-complexity digesters. Although this sort of system is frequently used in China and India, it cannot be used in crowded metropolitan or semi-urban areas due to a lack of space (Englund & Strande, 2019; Strande & Brdjanovic, 2014).

A Bio-methane Potential (BMP) test can be performed to determine whether an anaerobic digester is a suitable FS treatment technology. The largest amount of methane gas that may be created from a unit of volatile solids is the test's result (alternatively per unit wet mass, or COD, or total solids - TS). The BMP test is carried out on a small scale in a laboratory and tracks the daily methane production until less than 1% of the overall gas production is remaining, which typically takes 20 to 30 days (Drosg et al., 2013).

According to one BMP value from research, primary sludge from a wastewater treatment plant has a BMP value of 358.4 mL/g VS, while FS from pit latrines has an average BMP value of 50.6 ± 19.4 mL/g VS (Rose et al., 2015).

It's crucial to maintain a C:N ratio between 20:1 and 30:1, as well as a pH between 6.8 and 8.2 while it is running. Co-digestion is a practical solution as a result. Other organic waste streams, such as brewery waste, leftover grain, market garbage can be digested along with FS. The digestion might improve and variability might be decreased (Strande & Brdjanovic, 2014).

3 METHODOLOGY

3.1 Description of the study areas

The study was carried out in MUARIK that is located on spatial coordinates 0˚27'60"N, 32˚36'24" E at an altitudinal range of 1250 m to 1320 m above mean sea level (Okiror et al., 2017). The institute is found on the Gayaza-Zirobwe road, some 21 kilometers north of Kampala. With average maximum temperatures of 28.5 ^{0}C and minimum temperatures of 14 ^{0}C, MUARIK has a typical tropical climate.

3.2 Research Design

3.2.1 Reactor tests

The reactors were filled with inoculum from a field scale digester at the Waste Management Centre in MUARIK to a working volume of 18 liters and water chambers with water and studied for a week to observe the efficiency. The reactors were set at different temperatures and samples of inoculum were collected daily to assess for temperatures (Figure 11Figure 11). It was seen that there was a temperature difference between the reading on the temperature control panel and the actual temperature in the digester of 10^{0} C. This meant that to attain the required temperature the value on the control panel had to be set at 10^{0} C more.

Figure 11: Digestor testing

3.2.2 Experiment design and setup

FSC was collected from Lubigi Wastewater Treatment Plant and transported to MUARIK where the setup of the experiment was to be placed. The CW was collected from markets around Gayaza in a random manner and size reduction (mechanical pretreatment) done at Ento Organic Farm during sample preparation. Laboratory batch reactors with a total volume

of 20 liters were used. The reactors were made of stainless steel for the inner and mild steel for the outer layer. The reactor had suitable arrangements for feeding, gas collection, and draining of residues (digestate). Each reactor's effective (working) volume was maintained at 18 liters. The digestate that was collected from a field scale digester at the Waste Management Centre in MUARIK was used as the inoculum. The experiments were conducted at a substrate-to-inoculum (S/I) ratio of 1:3 since the substrate contained a low C/N ratio. The inoculum was sieved (Figure 12) before used to remove unwanted solid particles.

The substrates were mixed with inoculum and water while maintaining the volatile solids content of 8% (Song et al.,2012) in buckets for the combinations of mixing percentages of 75F:25C, 25F:75C, 50F:50C, and 100F. For each combination samples for laboratory analysis were collected using small water bottles and stored in the fridge. Upon loading the reactors pure nitrogen gas was purged into the reactor for 5 minutes as shown the (Figure 12) to eliminate oxygen traces and assure anaerobic conditions. The reactors were then sealed with a rubber stopper, silicon, and an aluminum cap, and nitrogen was purged through the gas taps. The experiments were left to settle for one day after which the gas taps were opened to let out excess Nitrogen and the pressure that could have been generated during purging. The gas tubes were then connected to trap the biogas (Figure 13). The reactors were stirred manually using a stirrer once daily to ensure homogenous conditions and set to a working thermophilic temperature of 55±5°C (Ryue et al., 2020) .The treatments were labeled A, B, D, E where A represented 50F:50C, B represented 75F:25C, D represented 25F:75C, and E represented 100F.

Figure 12: A- Inoculum Sieving, B-Nitrogen purging

Figure 13: Digester arrangement and connections

3.2.3 Digester feeding

A halted feeding method (batch feeding) was employed. This entails filling the digester all at once and keeping it closed for the duration of the retention period. The following steps were done when feeding the digester.

Calculations

Assuming a VS of 8%

Working volume = 18 liters ≈ 18000kg

Total mass = 0.08*18000 = 1440 g

Therefore; 1440 g is equivalent to 8% VS.

To get the total mass of substrate to be used in the reactors, we get 1440 g / VS % of the different combinations.

For example, for the ratio 100F

Thus, 1440/0.443 = 3251 g.

Therefore 3251 g is the total mass of substrate to be used in the reactor. The rest of the calculated values are shown in Table 2.

Table 2: Digester Feeding values for biogas production.

FSC:CW	Average VS (%)	Weight of FSC (g)	Weight of CW (g)
50F:50C	55.8	1290.5	1290.5
75F:25C	53.8	2008	669
100F	44.3	3251	0
25F:75C	57.7	624	1872

3.3 Substrate characterization

Samples of FSC and CW were taken to the laboratory and characterized based on the selected nutrients, pathogens, and heavy metals composition.

3.4 Moisture Content, Total Solids, Ash content and volatile solid determination

The total solid (TS), volatile solids (VS), moisture content (MC) and Ash content of the substrates were determined first on wet basis. The oven dry method was used for determination of moisture content where the wet samples were weighed before drying them in an oven. The samples were then placed into an oven for 24 hours and heated to temperatures of 105 ◦C, the samples were removed, left to cool in a desiccator, and then weighed again to determine the amount of lost. The moisture content on dry and wet basis was calculated from Equation 1 and Equation 2 respectively. The mass of the solids was recorded on the Data and calculations sheet. Then the MC can be obtained from the below.

$$MC_{dry} = \frac{Ww - Wd}{Wd} * 100\% \quad \text{.....Equation 1}$$

$$MC_{wet} = \frac{Ww - Wd}{Ww} * 100\% \quad \text{..... Equation 2}$$

Where, MC_{dry} = moisture content on dry basis, MC_{wet} = moisture content on wet basis, W_w= wet weight and W_d= dry weight

Then the TS can be obtained from the below.

$$\%TS = \frac{W1 - W2}{W3 - W2} \times 100 \quad \text{..... Equation 3}$$

Where, %TS = Percentage total solid

W1 = Weight of dried crucible + dried residue

W2 = Weight of crucible

W3 = Weight of wet sample (substrate) + crucible

The volatile solids (%) were obtained from the solid remaining after evaporation were dried, weighed, and ignited at 550°C for 6 hours in a Carbolite muffle furnace (UK) serial number 20-503092. The crucible and black mass of carbon were allowed to cool partially while in the furnace before it was transferred to the desiccator for complete cooling. The sample and desiccator weight were obtained. The percentage volatile solid was calculated using below

$$\%VS = \frac{W1-W4}{W1-W2}\times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

Equation 4

where,

%VS = Percentage of Volatile solid

W4 = Weight of crucible + weight of residue after ignition

3.4.1 Nutrients

The samples were then analyzed for nutrients at the School of Agricultural Sciences, College of Agricultural and Environmental Sciences, Makerere University using methods based on standard methods.

Table *3*: Standardized procedures used for characterization.

Parameters	**Tools and equipment**	**Reference**
Nitrogen (N)	Kjeltech block digestion and steam distillation unit	(Okalebo et al., 2002)
Phosphorous (P)	Hewlett-Packard 8452A Diode Array Spectrophotometer	(Okalebo et al., 2002)
Potassium (K)	Varian Spectra AA-200 atomic absorption spectrophotometer	(Okalebo et al., 2002)
Carbon (C)	Block digester tubes and the concentration	(Okalebo et al., 2002)

3.4.2 pH determination

The pH of each substrate was measured using a pH meter and similarly, the pH of the different ratios was also measured before the experiment was set up. 5g of FS and CW samples were weighed separately and 10 ml of water was added to each sample, and it was carefully stirred for 10 seconds using a rod. pH electrode was immersed into the suspension and reading was taking when it was steady. pH was measured before, during and after the digestion process.

3.4.3 Pathogens

Bacteriological media and bacterial cultures preparation

Media preparation

For carbapenem resistant Escherichia coli (CRE), metheglin resistant staphylococcus aureus (MRSA), and Salmonella isolation, Chromocult Coliform Agar and MacConkey Agar, Mannitol salt agar (MSA), and XLD medium were utilized, respectively. These were made according to the MSA agar manufacturer's instructions.100 grams of medium will be carefully mixed in 1000 mls of distilled water. The mixture was then heated to completely dissolve the medium before being chilled to 45 °C. 53.13 grams of medium were placed in the conical flask, followed by 100 mls of distilled water, and gently mixed. The mixture was then heated to allow complete media dissolution before being chilled to 45 °C. Both media were then autoclaved at 121°C for 15 minutes to sterilize them. After that, the mixture was allowed to cool to 45 °C. 20 mls of each media were then aseptically poured into petri plates and allowed to harden for around thirty minutes before being transferred to a 37 °C incubator for 24 hours of sterility testing.

Total coliforms, E. coli, and S. aureus enumeration

Following the tenfold serial dilution, 1 g of the test sample was dispersed in 9 mL of buffered 0.9% NaCl peptone water with surfactant Tween (pH =7) and diluted to 10-2 and 10-3 of the original concentration in the same buffer. A Pulsipher was then used to homogenize the mixture, resulting in a homogeneous mixture.

Salmonella inoculation on sterile medium plates with selective pre-enrichment

After 24 hours, 1 ml of the culture broth was placed into 9 mls of Rappaport and incubated at 42 °C for selective salmonella pre-enrichment. Using a sterile loop, the culture broth

containing the material was streaked over a CA and MSA and aerobically incubated at 37 °C for 24 hours.

After 24 hours, 1 ml of the culture broth was changed into 9 mls of Rappaport and incubated at 42 °C for 24 hours for selective pre-enrichment of salmonella and shigella, followed by streaking onto XLD plates and aerobically incubated for 24 hours.

Characterization of colony morphology and sub-culturing

The plates were examined after 24 hours for colonies of suspicious bacteria. Purple colonies in CA were presumed to be E. coli and were selected and sub-cultured onto MacConkey agar plates before being aerobically incubated at 37 °C for 24 hours. Medium-sized yellow colonies cultivated on MSA were presumed to be S. Aureus, and the colony forming units were counted and documented subsequently. On XLD, medium sized, pink colonies with dark centers were suspected to be salmonella. Then the colony forming units per gram (CFU/g) was calculated based on Equation 6.

$$\frac{CFU}{g} = \frac{N}{dF\,x\,V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 6}$$

Where;

N= number of colony counts

dF = Dilution factor

V = Volume of the plate

3.4.4 Heavy metals

Initially, sludge or co-mixed samples were dried in an oven at 105+5°C until all moisture was lost. Then the samples were milled using a ball mill to fine fractions. Milled sample fraction was filled in a cuvette and readings taken directly using XRF machine. In the end, readings (in mg/kg dry matter) were stored and obtained directly as XRF provides all the readings at once without the need to make separate decisions.

Correlation analysis was conducted to establish the nature of relationship, level of significance between concentrations of heavy metals in different samples.

3.5 Gas collection and measurement

The gas was collected using car tire tubes for the two digesters and using gas bags of 40 liters capacity for the other two. In both scenarios, the tubes and bags were inflated after reaching their capacity and an average gas volume estimated as shown in Equation 5.

$$Average\ gas\ volume = \frac{Volume\ of\ the\ bag\ (tube)}{Number\ days\ taken\ ¿}\ fill\ the\ bag\ (tube)\ ¿\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

Equation5

3.6 Biogas composition

Biogas composition was measured using a gas analyzer as described by Zhang et al, (2018). Biogas samples were taken using urine bags from the reactors (Figure 14Figure 14). The analyzer has two tubes, the inlet which is connected to opening of the urine bag and the outlet pipe for passing out the used gas.

Figure 14:Urine bags containing biogas.

4 RESULTS AND DISCUSSIONS

4.1 Characteristics of FSC and CW

The results of varying the ratios of FSC and cabbage waste are shown in the Table 4 along with the percentages of each parameter's composition, including pH, nitrogen (N), phosphorus (P), potassium (K), organic carbon (OC), organic matter (OM), moisture content (MC), dry matter (DM), ash, and volatile solids (VS).

All the ratios of fecal sludge to CW were examined: that is 50F:50C, 75F:25C, 25F:75C and 100% F and 100% C. Table 4 displays the outcomes for all the ratios, which were examined in three replicates.

The overall findings reveal that the mixtures and substrates had a pH between 6.02 and 8.05, indicating a mildly acidic to alkaline mixture. N, P, and K contents varied from 1.68 to 2.87%, 0.31 to 1.69%, and 0.91 to 5.06% respectively. While the MC content ranged from 65.60% to 90.97%, the OM content was considerable, ranging from 14.61% to 22.60%. In contrast to the ash content, which varied from 26.88% to 61.50%, the VS content ranged from 38.50% to 73.13%.

Table 4: Characterization of FSC and CW (mean ± standard deviation, n=3)

Particulars	DM (%)	Ash (%)	VS (%)	pH	N (%DM)	P (%DM)	K (%DM)	OC (%DM)	MC (%DM)
50F:50C	23.67 ± 0.25	44.23 ± 0.86	55.77 ± 0.81	6.48 ± 0.05	2.05 ± 0.03	1.29 ± 0.04	1.69 ± 0.02	10.03 ± 0.31	76.33 ± 0.25
75F:25C	27.1 ± 0.25	46.17 ± 0.37	53.83 ± 0.37	7.13 ± 0.08	2.21 ± 0.13	1.65 ± 0.03	1 ± 0.09	10.63 ± 0.42	72.9 ± 0.25
25F:75C	18.9 ± 0.10	42.3 ± 0.16	57.7 ± 0.16	6.60 ± 0.02	1.92 ± 0.15	1.11 ± 0.06	2.91 ± 0.24	11 ± 0.85	80.5 ± 0.85
100C	9.94 ± 0.65	27.58 ± 0.68	72.43 ± 0.68	6.1 ± 0.06	1.82 ± 0.10	0.34 ± 0.03	4.52 ± 0.69	14.58 ± 1.13	90.06 ± 0.65
100F	32.99 ± 1.01	55.73 ± 4.15	44.27 ± 4.15	7.98 ± 0.07	2.83 ± 0.09	1.65 ± 0.43	1.39 ± 0.17	9.44 ± 0.66	67.01 ± 1.01

4.2 Characteristics of sample

The sample refers to the combination of substrates, water and inoculum that were collected on the day of mixing. Here the anaerobic digestion treatment combinations of fecal sludge and cabbage waste for moisture content, dry matter, ash content, and volatile solids are examined as shown in the Table 5. The mixture of 50F:50C has the maximum volatile solids and moisture content, indicating its potential for anaerobic digestion. The lowest volatile solids and largest ash concentration are found in the 100F treatment, which suggests lower suitability. The treatments at 75F:25C and 25F:75C are intermediate between the two. These

findings provide information on feedstock composition, can improve anaerobic digestion procedures, increase the generation of biogas and the effectiveness of waste treatment.

Table 5:Characterization of sample (mean ± standard deviation, n=3)

Sample code	MC (%)	DM(%)	Ash (%)	VS(%)	pH	Temp
50F:50C	97.26 ± 0.08	2.74 ± 0.07	28.43 ± 0.50	71.57 ± 0.50	7.15 ± 0.00	25 ± 0.0
75F:25C	96.37 ± 0.03	3.63 ± 0.03	31.62 ± 0.70	68.38 ± 0.70	7.20 ± 0.01	25 ± 0.0
25F:75C	96.83 ± 0.06	3.17 ± 0.06	28.62 ± 1.00	71.38 ± 1.00	6.97 ± 0.01	25 ± 0.0
100F	94.88 ± 0.06	5.12 ± 0.06	35.12 ± 0.90	64.88 ± 0.90	7.59 ± 0.01	25 ± 0.0

4.3 The pH of different mix ratios at various stages

The pH of different mix ratios was determined before setting up the experiment, pH was measured before, during and after the digestion process. The results for the pH at different stages of the mix ratios are shown in Figure 15. The pH remained in the recommended range throughout the whole experiment similar to that by (Liu et al., 2022).

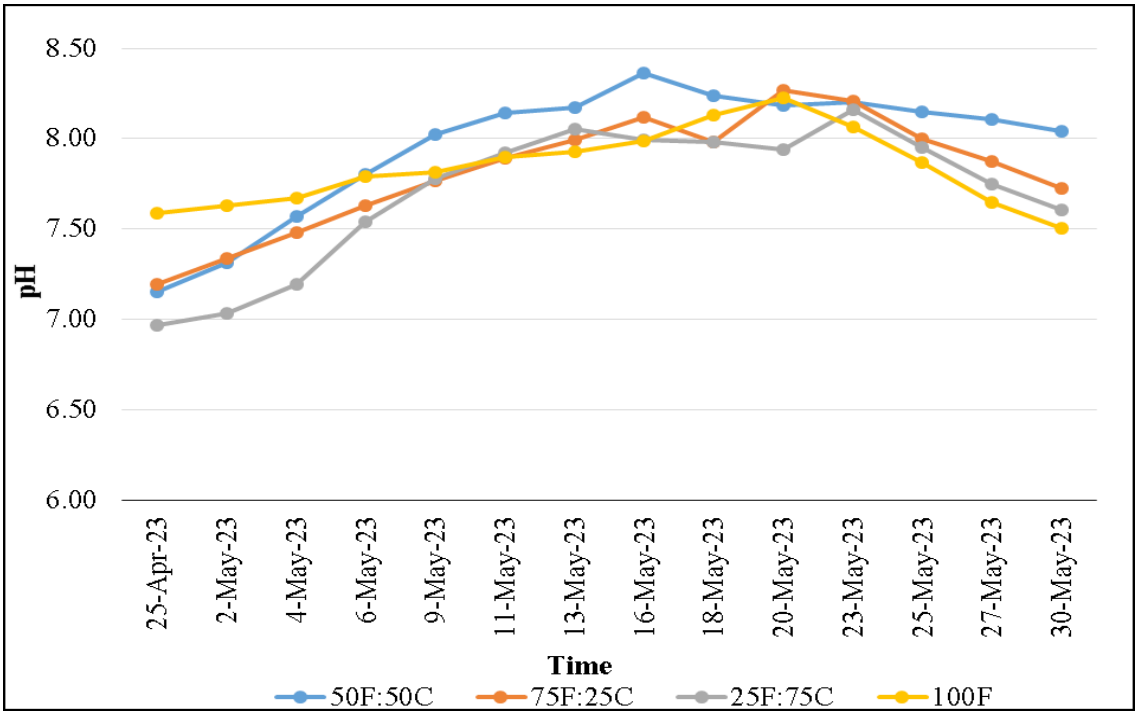


Figure 15:pH variation during the study

4.4 Pathogen characterization

The study of three pathogens, e-coli, staph, and salmonella was conducted before (Table 6) and after the experiment. The pathogens were present in the initial characterization, but they were destroyed by the high temperatures that were maintained for the entire experiment.

Table 6: Initial pathogen characterization

Treatments	E-coli (cfu/g)	Staph (cfu/g)	Salmonella (per 25g)
50F:50C	3.54 ± 0.03	4.25 ± 0.02	Not detected
75F:25C	4.60 ± 0.02	4.32 ± 0.02	Not detected
25F:75C	3.61 ± 0.02	3.34 ± 0.02	Not detected
100F	4.64 ±0.15	4.43 ± 0.26	Not detected

4.5 Concentration of heavy metals in fecal sludge and the digestate

The concentration of heavy metals in fecal sludge and digestate are shown in the Table 7. The dataset being presented includes a thorough collection of metal concentrations, expressed in mg/kg for various parameters. Initial F0 and final conditions, specifically 75F:25C and 100F, as well as at 25FS:75C, were the two different conditions under which these parameters were measured. This dataset is essential for determining how these metal concentrations alter under these circumstances and offers information about potential system changes that might take place.

Table 7: Heavy metal values

	Initial	Final		
Metal (mg/kg)	**F0**	**75F:25C**	**100F**	**25F:75C**
Mo	7.9	8.2	9.9	9.1
Zr	162.0	130.8	172.6	103.2
Sr	140.7	187.7	192.2	191.9
Rb	25.6	125.2	85.0	139.9
Th	2.6	2.8	3.8	2.8
Pb	18.6	22.9	25.6	18.2
Zn	713.4	883.5	1017.0	2436.9
Cu	93.0	141.7	128.6	104.3
Fe	21743.5	20169.7	22220.9	17118.1
Mn	385.6	579.4	558.4	464.4
V	81.4	72.6	74.9	66.1
Ti	2911.2	2817.4	3269.6	2193.9
Sc	59.6	51.6	54.6	59.7
Ca	32492.8	40585.2	42958.8	37960.8
K	7107.8	37343.6	22533.2	44825.5
S	5171.7	5140.2	5043.6	4720.6
Nb	17.5	15.6	16.7	13.2
Bi	5.7	6.8	10.8	9.6
Al	10019.4	14394.2	14499.2	14566.5
P	12460.3	14127.6	15043.0	13104.2
Si	96201.3	56852.8	64669.6	55621.2
Cl	3171.2	8046.5	5278.2	8525.2
Mg	2556.7	10861.8	2820.9	9459.3

Initial-Heavy metal values before the experiment, Final- Heavy metal values after the experiments were run, F0-Initial fecal sludge cake sample that was characterized before the experiment

Mo concentrations show a modest increase from the initial to the final conditions, with the condition at 100F showing the largest increase. In the 25FS:75C condition, Zr concentrations drop. Sr concentrations follow a predictable pattern, slightly rising at 100°F. The 25F:75C condition exhibits the greatest increase in Rb concentrations overall. Th concentrations fluctuate very little and remain stable. Apart from the 25FS:75C condition, where concentrations decrease, Pb levels gradually rise. Zn concentrations rise under all final conditions, with the 25FS:75C condition experiencing the greatest rise. In the 100F condition in particular, the concentrations of Cu decrease. Fe concentrations drop, with the temperature of 100F experiencing the biggest drop. Mn concentrations rise, with the maximum rise occurring at 75F:25C. S concentrations exhibit minute variations, with a decline at 100°F. Nb concentrations are declining, Bi concentrations are rising, Al concentrations are rising, and P concentrations are barely changing. All final conditions show a noticeable increase in magnesium concentrations, with the 75F:25C condition showing the largest increase.

4.5.1 Correlation of heavy metals level in different samples

The provided correlation matrix (Table 8) identifies important correlations and contrasts in the concentrations of metals in the investigated system. Significant positive correlations between elements like Bi-Mo, Sr-Ca, K-Zn, and Pb-Cu have been found, pointing to a possible interconnection between the heavy metals. This suggests that metal pairs in FS and digestate samples may have had a common source of heavy metal pollution, likely anthropogenic activities (Kinuthia et al., 2020). Negative correlations like V-Nb, Fe-Al, Ca-Cl, and Mn-Zn suggest distinctive behaviors or rivalry.

Table 8: Heavy metal matrix

	Mo	*Zr*	*Sr*	*Rb*	*Th*	*Pb*	*Zn*	*Cu*	*Fe*	*Mn*	*V*	*Ti*	*Sc*	*Ca*	*K*	*S*	*Nb*	*Bi*	*Al*	*P*	*Si*	*Cl*	*Mg*
Mo	1																						
Zr	0.106	1																					
Sr	0.700	-0.405	1																				
Rb	0.344	-0.782	0.876	1																			
Th	0.884	0.496	0.548	0.077	1																		
Pb	0.523	0.544	0.497	0.090	0.824	1																	
Zn	0.395	-0.800	0.498	0.673	-0.076	-0.457	1																
Cu	0.243	0.044	0.672	0.506	0.449	0.812	-0.264	1															
Fe	-0.032	0.978	-0.416	-0.754	0.408	0.577	-0.904	0.162	1														
Mn	0.432	0.000	0.799	0.593	0.575	0.831	-0.110	0.978	0.081	1													
V	-0.434	0.836	-0.814	-0.950	-0.062	0.100	-0.868	-0.241	0.865	-0.369	1												
Ti	0.161	0.946	-0.170	-0.570	0.594	0.765	-0.841	0.365	0.967	0.314	0.709	1											
Sc	-0.077	-0.176	-0.490	-0.331	-0.366	-0.808	0.462	-0.975	-0.317	-0.910	0.037	-0.483	1										
Ca	0.717	0.033	0.889	0.596	0.780	0.839	0.073	0.848	0.043	0.938	-0.458	0.297	-0.731	1									
K	0.281	-0.852	0.818	0.993	-0.024	-0.032	0.731	0.409	-0.827	0.493	-0.966	-0.666	-0.234	0.495	1								
S	-0.507	0.721	-0.537	-0.650	-0.047	0.374	-0.991	0.248	0.843	0.077	0.854	0.764	-0.454	-0.142	-0.698	1							
Nb	-0.260	0.933	-0.641	-0.879	0.163	0.346	-0.925	-0.034	0.963	-0.146	0.968	0.864	-0.154	-0.220	-0.925	0.889	1						
Bi	0.988	-0.046	0.769	0.468	0.814	0.448	0.516	0.244	-0.180	0.441	-0.565	0.020	-0.057	0.721	0.414	-0.616	-0.403	1					
Al	0.659	-0.428	0.998	0.892	0.512	0.490	0.485	0.695	-0.428	0.813	-0.818	-0.183	-0.517	0.885	0.835	-0.518	-0.649	0.732	1				
P	0.681	0.323	0.717	0.336	0.865	0.959	-0.189	0.836	0.335	0.902	-0.179	0.564	-0.770	0.956	0.220	0.104	0.075	0.640	0.708	1			
Si	-0.507	0.595	-0.966	-0.966	-0.317	-0.338	-0.553	-0.657	0.572	-0.756	0.887	0.348	0.482	-0.784	-0.928	0.558	0.755	-0.604	-0.977	-0.568	1		
Cl	0.202	-0.845	0.797	0.989	-0.069	-0.010	0.658	0.468	-0.796	0.531	-0.930	-0.638	-0.309	0.494	0.994	-0.616	-0.888	0.334	0.821	0.225	-0.923	1	
Mg	-0.180	-0.864	0.545	0.861	-0.387	-0.166	0.473	0.421	-0.756	0.407	-0.753	-0.665	-0.330	0.252	0.885	-0.389	-0.768	-0.046	0.585	0.003	-0.742	0.926	1

4.6 Biogas composition

The biogas composition was determined in week 1, 2, 3, 4, and 5. The results obtained using the gas analyzer a shown in Table 11: Biogas composition. For each treatment, routine gas measurements including CH4, CO2, O2, and balance percentages were taken. The data revealed significant differences in the content of methane between the various treatments and weeks. Generally, the contents of methane and carbon dioxide, two main components of biogas, ranged from 6-69.3% and 11-62.8% respectively. The 75F:25C treatment continuously showed greater methane levels during the whole five-week observation period, according to careful analysis. For this treatment, the respective methane percentages for Weeks 1 through 5 (Figure 16,Figure 17) were 21.1%, 61.1%, 57.2%, 62.8%, and 55.3%. The 75F:25C treatment demonstrated the potential for increased methane production when mixed with cabbage waste since there was a higher percentage of fecal sludge in the feedstock mixture.

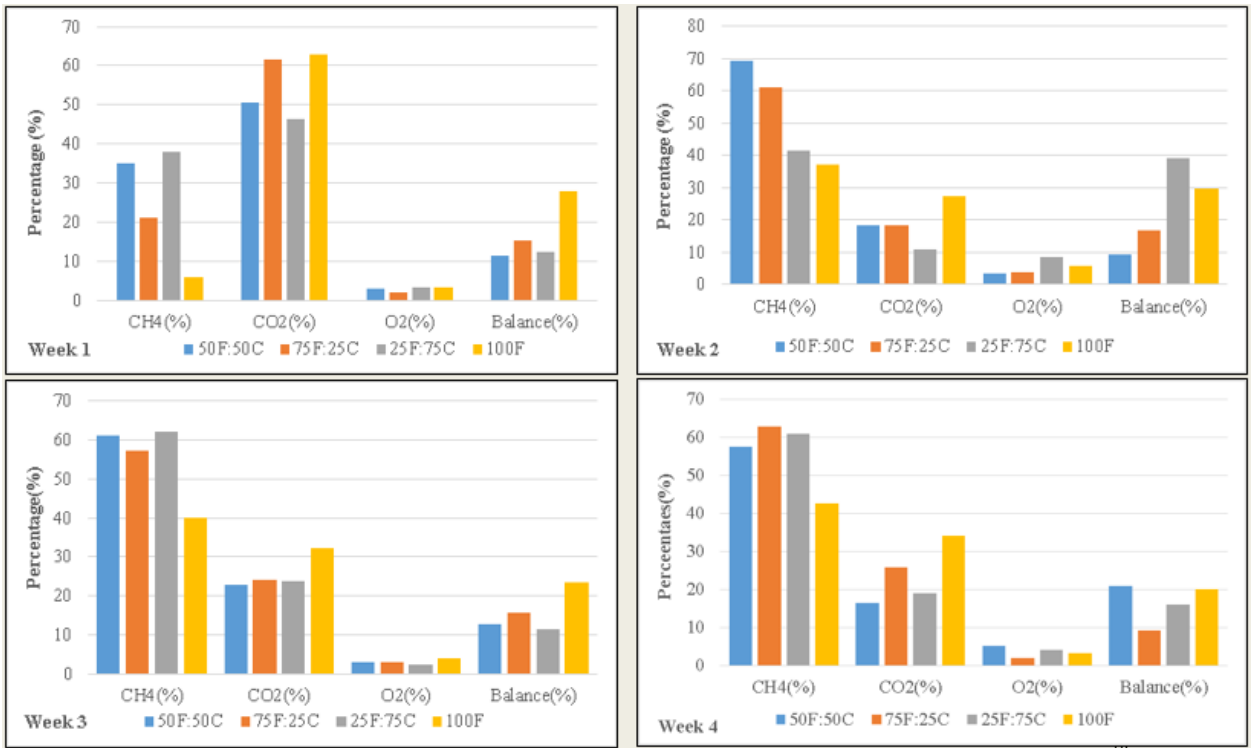


Figure 16: Biogas percentages for week 1 to week 4

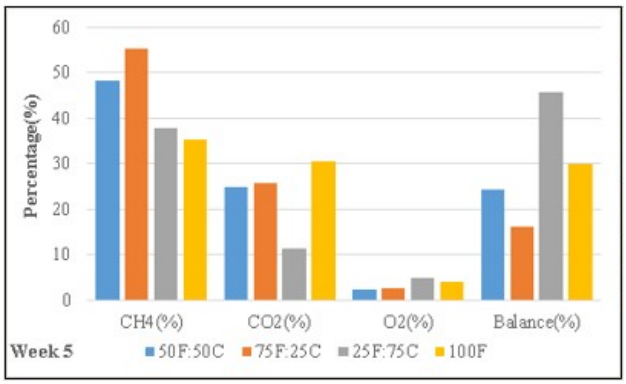
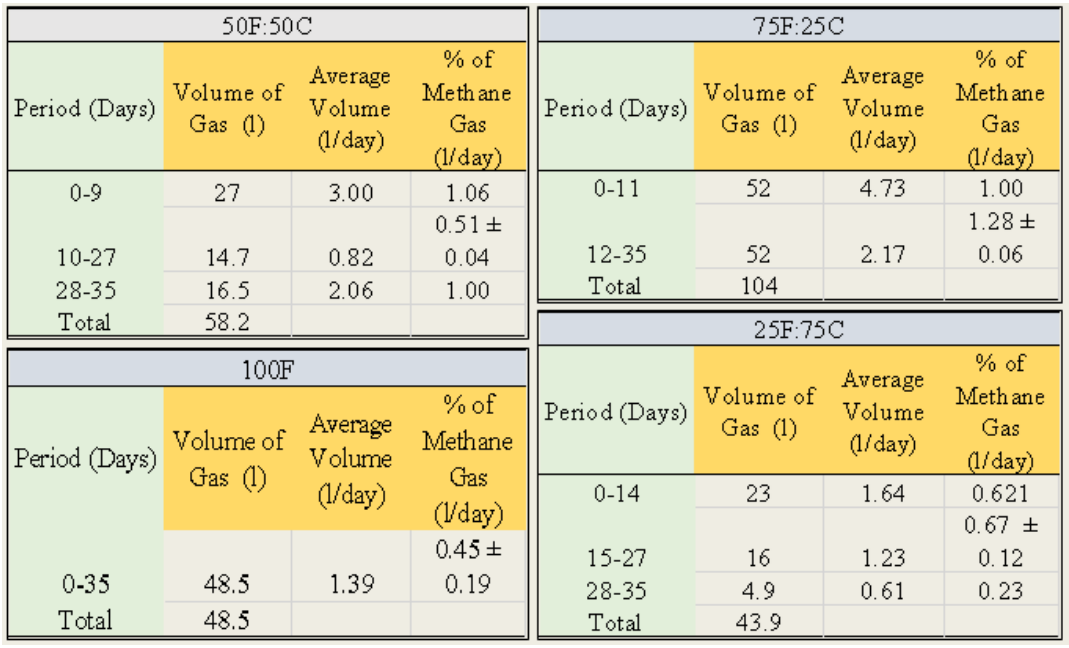


Figure 17:Biogas percentage for week 5

4.7 Methane yield from fermentation

The average methane volume (Figure 18) was calculated based on the volume of gas that was collected over a given period and the following tables were obtained. Based on the average methane produced treatment 75F:25C had the highest volume with values ≥1 l/day and highest methane percentage followed by treatments 50F:50C, 25F:75C, and lastly 100F.



50F:50C

Period (Days)	Volume of Gas (l)	Average Volume (l/day)	% of Methane Gas (l/day)
0-9	27	3.00	1.06
10-27	14.7	0.82	0.51 ± 0.04
28-35	16.5	2.06	1.00
Total	58.2		

75F:25C

Period (Days)	Volume of Gas (l)	Average Volume (l/day)	% of Methane Gas (l/day)
0-11	52	4.73	1.00
12-35	52	2.17	1.28 ± 0.06
Total	104		

100F

Period (Days)	Volume of Gas (l)	Average Volume (l/day)	% of Methane Gas (l/day)
0-35	48.5	1.39	0.45 ± 0.19
Total	48.5		

25F:75C

Period (Days)	Volume of Gas (l)	Average Volume (l/day)	% of Methane Gas (l/day)
0-14	23	1.64	0.621
15-27	16	1.23	0.67 ± 0.12
28-35	4.9	0.61	0.23
Total	43.9		

Figure 18: Volume of biogas

4.8 Analysis nutrients for their suitability for crop growth

The digestate was characterized for N, P, K, OC (Error: Reference source not found), heavy metals (Table 7) and pathogens (Table 10) and compared with the known standards for organic fertilizers as per UNBS (2017) in Table 12,Table 13, and Table 14.

Table 9:Final nutrient characterization

Particulars	N (% DM)	P (% DM)	K (% DM)	Na (% DM)	OC (% DM)	C:N
50F:50C	0.16 ± 0.01	0.92 ± 0.07	3.18 ± 0.16	0.10 ± 0.01	8.55 ± 0.42	60.98 ± 2.46
75F:25C	0.19 ± 0.01	1.50 ± 0.16	2.84 ± 0.16	0.12 ± 0.01	11.74 ±0.21	56.24 ± 1.29
25F:75C	0.17 ± 0	1.23 ± 0.02	2.50 ± 0.16	0.08 ± 0.01	9.80 ± 0.05	55.19 ± 1.46
100F	0.12 ± 0	1.99 ±0.07	2.39 ± 0	0.14 ± 0.01	12.29 ±0.27	61.65 ± 1.18

Table 10: Microbial Characterization

Treatments	E-coli (cfu/g)	Staph (cfu/g)	Salmonella (per 25g)
50F:50C	0.00	0.00	Not detected
75F:25C	0.00	0.00	Not detected
25F:75C	0.00	0.00	Not detected
100F	0.00	0.00	Not detected

The nutrients are in the recommended range, which is not the case with the C:N ratio for all the treatments. The pH was also in the appropriate range. Since all the pathogens were eliminated, the digestate was within the recommended limit for the pathogens. For heavy metals, Pb and Cu were less than the limit which presents a possibility of using the digestate as a fertilizer.

5 RECOMMENDATIONS AND CONCLUSIONS

In summary, this study explored the potential of anaerobic co-digestion of fecal sludge and cabbage waste for biogas production and nutrient-rich digestate generation. The optimized substrate ratio of 75F:25C significantly increased biogas yields. While the resulting digestate demonstrated suitable nutrient concentrations for crop growth, the elevated C:N ratio indicated a need for further processing before use as a fertilizer.

To enhance operational resilience in waste management systems, the incorporation of an emergency power source is essential. The study recommends investigating organic stabilizers to bolster system robustness. Further research could focus on understanding microbial interactions in the 75F:25C substrate mixture, potentially optimizing methane yield.

Notably, the digestate's low heavy metal concentrations, particularly Pb and Cu, position it as a promising organic fertilizer. Process optimization, exploration of microbial dynamics, and C:N ratio adjustments are avenues for further refinement. Field trials assessing the digestate's impact on crop growth, yield, and soil health can validate its effectiveness. Scaling up the anaerobic digestion process for urban waste management systems will provide insights into economic and environmental sustainability on a larger scale.

In conclusion, this study advances sustainable waste management practices, biogas production, and agricultural resource recovery. Future research should focus on optimizing the co-digestion process, investigating microbial dynamics, and assessing the digestate's impact in field trials and urban waste management systems.

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7 APPENDIX

Table 11: Biogas composition

Treatments	Period	Week 1	Week 2	Week 3	Week 4	Week 5
50F:50C	CH_4(%)	35.2	69.3	61.2	57.5	48.3
	CO_2(%)	50.6	18.2	22.8	16.5	25
	O_2(%)	2.8	3.5	3.1	5.1	2.3
	Balance(%)	11.4	9.5	12.9	20.9	24.3
75F:25C	CH_4(%)	21.1	61.1	57.2	62.8	55.3
	CO_2(%)	61.6	18.2	24	25.9	25.8
	O_2(%)	1.9	3.9	2.9	2.1	2.6
	Balance(%)	15.4	16.9	15.8	9.2	16.2
25F:75C	CH_4(%)	37.8	41.3	62.2	60.9	37.9
	CO_2(%)	46.3	11	23.7	19	11.4
	O_2(%)	3.3	8.6	2.5	4.1	4.9
	Balance(%)	12.5	39.2	11.6	16	45.7
100F	CH_4(%)	6	37.3	40.1	42.6	35.4
	CO_2(%)	62.8	27.4	32.3	34.2	30.6
	O_2(%)	3.3	5.8	4.1	3.2	4.2
	Balance(%)	28	29.6	23.6	20.1	29.9

Table 12:Contaminant limits for Organic fertilizers

S/N	Properties	Organic Fertilizer Limit	Test Methods
1	Total NPK (%)	5-7	ISO 11261, ISO 6598 and ISO 5318
2	C:N	12:1 - 15:1	-
3	Soluble salts (Conductivity), mmhos/cm, max.	5	ISO 11265
4	Total Nitrogen, %, m/m, min.	1	ISO 11261
5	Organic carbon,%, m/m, min.	12	ISO 10694
6	Moisture Content (Solid Organic fertilizer) (%), m/m	30-35	ISO 11465
7	p^H	6.0-10.0	ISO 10390
8	Stones >5mm size, %, m/m, max.	5	
9	Seed, number/kg, max	5	

Table 13: Microbiological limits for Organic Fertilizers.

Pathogens	Limit
Fecal Streptococci (cfu/g)	5×10^2
Total coliforms (cfu/g)	5×10^2
Salmonella	Absent
Infective parasites	Absent
Escherichia coli	Absent
Enterococci	Absent

Table 14:Contaminant limits for Organic fertilizers

Heavy Metals	Limit (mg/kg dry wt)	Test method
Arsenic (As)	10	ISO 17318
Lead (Pb)	100	ISO 17318
Mercury (Hg)	2	ISO 17318
Cadmium (Cd)	5	ISO 17318
Copper(Cu)	300	ISO 11047
Chromium(Cr)	50	ISO 17318

Figure 19:A-gas sample collection, B-Gas composition reading using a gas analyzer, C-Urine bags filled with gas samples, D &E Nutrient analysis, F-pH reading using a pH meter, G-Placing samples into the oven, H-Sample weighing.