Enhanced biogas production from human and agro-waste: Waste to wealth initiative

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Abstract

High population spikes have been projected for developing countries in the nearest future. This development is a source of concern as there are no visible futuristic economic agenda to douse the menace of population growth in a dying economy. This paper is a blueprint for standalone energy users and the built industry to improve energy generation using sustainable materials, i.e., human and agro waste. This research examines two popular agro waste i.e., plantain peel and Siam leave. The concept of bio-digester septic tank design (BDSTD) was also discussed. Biogas from plantain-faecal (PF) had a higher cumulative production than biogas from Siam-faecal (SF) because plantain biomass aids initial bio-digestion of the faecal samples due to its inherent chemical components which are important to breaking undigested food component in the faecal mass. In this wise, the chemical component in Siam biomass cannot easily break undigested food components in the faecal mass. However, SF creates a better enabling environment for microbial growth that could lead to about 400% biogas generation over PF and 160% biogas generation over pure faecal (TF). Despite this feat, the caveat for improved daily gas production rate in SF is hinged on pre-processing of the faecal mass. With the aid of machine learning, it was revealed that higher retention time could be a natural way of pre-processing needed by the Siam biomass. This concept led to the design of the BDSTD which was technically hinged on cross-sectional partitions. Plantain biomass is recommended for four partitions BDSTD design as there would be shorter retention time in the overflow chamber while the Siam biomass is recommended for >4 partitions BDSTD designs.

Keywords: Biogas, design, production, BDSTD, digester, energy

1. Introduction

Biogas production has gained global attention (Fig. 1). The high demand for a cleaner energy source in developing countries has increased in the last two decades. Unfortunately, most developing countries are richly blessed with untapped renewable sources with renewable energy still at the primary stage of development. A lack of reliable and affordable electricity supply has been a hindrance to industrialization as both private and publicly owned businesses often depend on fossil-fuel generators for sufficient power. Aside from this, the increased use of generating sets has also contributed to the emission of greenhouse gases which in turn contribute to causing global warming. Scientists have reported that the rehabilitation of the power sector in developing countries would be to improve energy access at a reduced cost for end users.

Biogas technology provides a means to generate gases that can be combustible. Biogas is primarily comprised of methane (CH_4), and carbon dioxide (CO_2) and may or may not have small amounts of H_2S, moisture, and siloxanes. Generally, the energetic value of the biogas increases with a higher methane content that allows the combustion of the formed biogas (Deublein and Steinhauser, 2011; Perera, 2018; Mukherjee *et al*., 2020).

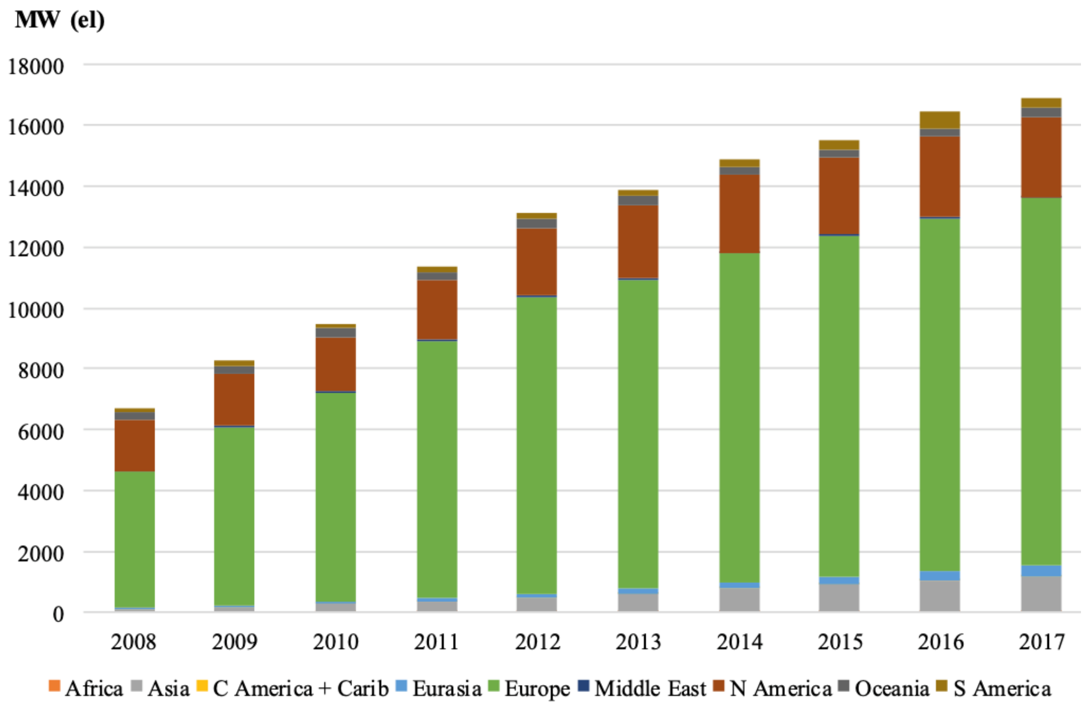


Figure 1: Globally installed electricity capacity by biogas plants by region over time (IRENA, 2018)

Biogas is made by a reaction known as anaerobic digestion. A biogas bioreactor is made in such a way that it can turn biodegradable materials into biogas for use. The natural gas obtained from this process can be utilised in cooking, room heaters, water heating, and running automobiles. This process also provides a residue or remnant that can be converted to fertilisers for farms. The choice of domestic energy is usually based on the income of each individual or family. Moreso, most individuals would prefer to use cheaper alternatives to costly ones.

Hence, energy solutions that are generally acceptable are tied to the cost of purchase and their sustainability. Biogas is projected to have the prospect of meeting the above criteria based on the possibility of a low-cost bioreactor that is mainly the septic tank and the availability of animal and agro waste to complement its low cost. Animal waste has been seen to have a high methane content. This can be found in the human waste product too. However, the search for an effective way to extract pure methane from waste products has been a struggle, and the unavailability of animal or agricultural waste has brought the use of human waste to mind. Biogas generated from human waste or excreta can be considered beneficial, safe, and efficient for human use. From past research (Emetere et al., 2022a, b), it was indeed proven that agro-based products can be used in optimizing biogas from human excreta.

The focus of this research is to provide a cheap and sustainable source of biogas production from human and agro (Siam and plantain) waste. This initiative is projected to lift 25% of the populace in developing countries from the poverty level. The choice of human waste is because its sustainability depends on a large human population in developing countries whose annual population growth rate is about 2.5% (NPC, 2006). In section two, the microorganisms from human faecal samples were discussed and the metabolites produced by microorganisms from human faeces in section three. Material and reactor description was discussed in section four and the methodology in section five. The results were discussed in section six and the conclusion of the study in section seven.

2. Literature Review

Human faecal samples comprise diverse microorganisms that include bacteria, archaea, viruses, fungi, protozoans, and parasites (microbial eukaryotes) (Garcia-Aljaro *et al*., 2018). Bacteria and viruses are the most abundant groups of microbes in the human gut microbiota. Diverse reports reveal that microbiological profiles of fresh sewage show human gut microbiota. Additionally, human and animal faces share numerous commensal microorganisms including pathogens (Garcia-Aljaro *et al*., 2018). Bacterial microflora of healthy human faecal sample includes Shiga-toxin producing *Escherichia coli* (STEC), *Escherichia coli, Citrobacter, Klebsiella, Pseudomonas, Proteus, Enterobacter Salmonella* sp., *Shigella* sp., *Campylobacter* sp., *Streptococcus faecalis* and *Bifidobacterium* sp. and *Yersinia* amongst others and some Gram-positive members comprising of *Enterococcus, Streptococcus, Bacillus, Lactococcus* and others. The large intestine houses the most common normal bacterial flora which include anaerobes (*Bacteroide*s, Gram-positive rods and Gram-positive cocci), Gram-negative enteric organisms and *Enterococcus faecalis.* A significant fungal population in stool samples is also obtained in food or the oral cavity and comprises of *Candida albicans, Saccharomyces cerevisiae, Penicillium citrinum, Aspergillus niger, Phoma herbarum, Geotrichum candidum* but the first two isolates are the predominant fungal agents regularly detected in stool samples of healthy humans (Auchtung *et al*., 2018). The most numerous and diverse domain is the bacterial groups with most members residing in the human gastrointestinal tract. Studies have revealed that Bacteroidetes (i.e. *Bacteroides* and *Prevotella*) and Firmicutes (i.e. *Clostridium*, Lachnospiraceae; *Ruminococcus*, and *Enterococcus*) are the prevalent ones that account for more than 90% while members of Proteobacteria (i.e. *Escherichia coli*, *Acinetobacter*, *Pseudomonas*, *Aeromonas* among others), though also prominent and differential, constitute only 0.1% of the total proportion. The most common yeast species isolated from faeces of healthy children and adult humans is *C albicans* with identification from 65% of adult stool samples (Forbes *et al*., 2001).

According to the studies of Kumari and Ambasta (2013), the bacteria isolated from diarrhoeic faecal samples of humans include *Escherichia coli*, *Vibrio cholerae*, *Enterobacter aerogenes* and *Klebsiella pneumonia*. The Archaea are identified by reduced diversity and concentrations (108 cells per ml) compared to the bacterial ratio (Garcia-Aljaro *et al*., 2018) while the yeasts and filamentous fungi are more reduced in diversity and the protozoans constitute the paramount microbial eukaryotes in the human gut of healthy persons (Hallen-Adams and Suhr, 2017). Viruses, mostly bacteriophages, represent another important proportion of the human gut microbiota in which their numbers in the gut or faecal samples are quite high (1 X 1010 virus-like particles (VLP) per ml) (Letarov and Kulikov, 2009). Despite all this immense diversity in the gut microbiota of humans, there are variations amongst individual persons that can fluctuate over time from one person to another due to age, genetics, environment, diet, and socioeconomic and cultural determinants. In furtherance, challenges associated with isolating these faecal aetiological agents include the low and fluctuating numbers of pathogens present in sewage, methodological difficulties with their detection and enumeration, the complexity of sample matrices, and the sampling process involved (Garcia-Aljaro *et al*., 2018).

Human faeces are nutrient-rich organic substrate that contains, bacterial biomass, water, polysaccharides, undigested fats, ash, proteins and undigested food residues (Karu *et al*., 2018). The bacterial biomass which comprises both dead and living bacteria contributes a significant proportion of dry solid and faecal mass (about 25–54%) (Abdel-Shafy and Mansour, 2018; Penn *et al*., 2018). High nitrogen composition in human faeces is a result of the protein content, unprocessed dietary protein, nucleic acids containing nitrogen (present as a result of the large mass of bacterial present in human faeces), secreted mucus containing sloughed intestinal mucosal cells (Canfield *et al*., 1963; Bender and Bender, 1997) and undigested protein present in the faeces (Volk and Rummel 1987). Human feces also contain lipids that come from bacterial biomass present in faeces, undigested dietary fat intake, and shredded intestinal epithelial mucosa (Wisniewski *et al*., 2019). Carbohydrate present is made up of pentosan, fibers and undigested cellulose except for nitrogenous materials (Afolabi and Sohail, 2017), present in large chains of polysaccharides that make digestibility difficult (Krueger *et al*., 2021). Also present in human faeces are inorganic matters, significantly made of iron phosphate and calcium phosphate, dried digestive juices in small quantities which include shredded epithelial cells, mucus, and intestinal secretions among others (Yan *et al*., 2020; Zhao *et al*., 2022).

Human faeces is composed of a large proportion of bacterial cells per unit gram of faeces, (Bellali *et al*., 2019) most of which are grouped into 400–800 species through sequential analysis (Ser *et al*., 2021). Some of these species are involved in anaerobic digestion (AD) of faeces which occurs naturally in septic tanks (Cyprowski *et al*., 2018). Anaerobic digestion is a biochemical process where organic wastes are converted by bacteria to convert organic wastes into methane and CO_2 gas mixture in a ratio of 3 to 2 called biogas (Greene, 2019). Methane, a highly beneficial greenhouse gas and source of energy are generally 25 times more potent than CO_2 (on a mass basis) over many years (EPA, 2021). Methane can be utilized as a storable energy carrier, a motor fuel, an electricity generator, or synthesising base chemical (Enzmann *et al*., 2018). Methanogens are the only microbes that produce large amounts of methane on earth (Alemneh, 2020). Methanogens are microbial communities that live in the human large intestine and possess the ability to produce methane which distinguishes the archaeal group of methanogens (Buan, 2018).

Only a few methanogens per gramme of dry weight (gdw) of faeces are excreted by humans which have been shown to include *Methanobrevibacter smithii*, *Methanosphaera stadtmanae*, and *Methanomassiliicoccus luminyensis*, all of which are methanogenic archaea (Knobbe *et al*., 2020; Amin *et al*., 2021). *Methanobrevibacter smithii* is the most common methanogen found in human faeces (Chong *et al*., 2019). *Methanosphaera stadtmaniae*, a coccus belonging to the Methanobacteriaceae family, that uses H2 to convert methanol to methane, is often seen in low concentrations (Camara *et al*., 2021).

Anaerobic digestion of human faeces includes the following steps hydrolysis, acidogenesis, acetogenesis, and methanogenesis, the first step is the hydrolysis and fermentation stage (Wainaina *et al*., 2019). In the hydrolysis stage, hydrolase enzyme secreted extracellularly by hydrolyzing bacteria hydrolyzes the complex organic matters such as proteins, lipids and water-insoluble carbohydrates into reduced water-soluble organic molecules that are proteins are hydrolyzed in amino acids, lipids to long-chained fatty acids and carbohydrates (Saber *et al*., 2021). Cellulose and hemicellulose are hydrolyzed by bacteria that include *Clostridium cellulovorans*, *Clostridium saudii* among others, protein is hydrolyzed by *Streptococcus gallolyticus*, fat might be hydrolyzed Pseudomonas caeni and starch hydrolysis might be performed by *Clostridium butyricum*, *Clostridium beijerinckii* among others, (Yang *et al*., 2019). The fermentation process also known as acidogenesis is characterized by fermentative bacteria fermenting monosaccharides to produce acids including *Terrisporobacter petrolearius*, *Turicibacter sanguini* among others, vis-a-vis amino acids and long chain fatty acids fermented by *Peptostreptococcus russellii* and *Clostridium butyricum* respectively. These constitute a bacterial community with fermentative, acid and hydrogen production abilities (Yang *et al*., 2019). These bacteria produce CO_2 from short-chain fatty acids (including lactic acid, propionic, acetic, or butyric acid) by fermentation (Annie Modestra *et al*., 2020). Hydrolyzing bacteria and fermentative bacteria are very important in hydrolytic fermentation as well as a metabolic pathway involved in biogas production so they are the initial rate-limiting factor for biogas fermentation (Cai *et al*., 2016).

The second stage of biogas production, the acetogenesis stage is characterised by the degradation of the short-chain fatty acids produced during the hydrolysis and fermentation stages by hydrogen-producing bacteria, to produce CH_3COOH and H_2, in certain scenarios, CO_2 can be produced from the reaction (Menzel *et al*., 2020.). Propionic acid-degrading bacteria (*Pelotomaculum schinkii*) and butyric acid/pentanoic acid-degrading bacteria (*Syntrophomonas zehnderi*), are most likely responsible for hydrogen production and acetogenic activity in some circumstances (Yang *et al*., 2019). Propionic, butyric, isobutyric and isopentanoic acids all require hydrogen-producing acetogens for conversion to acetate acid (Wainaina *et al*., 2019).

In the methanogenic stage of biogas production, methane is produced, through the conversion of various metabolites including acetic, propanoic, pentanoic, butyric acids (obtained from hydrolytic fermentation) derived from the breakdown of fatty acids, amino acids, and proteins by microbes to CH_4 through various pathways (Yang *et al*., 2019). Hydrogenotrophic methanogens which include facultative methanogens, produce CH_4 with the use of H_2 and CO_2 (Zhang *et al*., 2020). Acetic acid is used by nutrient-producing methanogens including *Methanosaeta concilii* and facultative methanogens which include *Methanosarcina soligelidi* to produce CH_4 (Yang *et al*., 2019). Methanogens, which are important in biogas fermentation, become particularly active near the conclusion of the biogas production pathway (Enzmann *et* *al*., 2018), implying that low temperature favours the growth of hydrogenotrophic methanogens (Yang *et al*., 2019). This also indicates that H_2 and CO_2 are the primary sources of CH_4 in this biochemical process (Paulo *et al*., 2015).

4. Materials and Methods

In this section, the materials used for this research will be discussed. The agro waste that was considered for the research was Siam weed and African plantain waste. The various design of a low-cost biogas reactor was also discussed in this section. The use of agro waste for this research is because of its abundance in the location of research. Unimaginable tones of agro waste emanating from Siam weed and African plantain peels are either burnt or thrown to dumpsites. In order words, this initiative is aimed at converting waste to wealth. More also, agro waste have been found to have other advantages such as: it is a natural optimizer; it is free of excessively harmful substances; it can be easily gotten; it is safe to use in a controlled environment; agro-based products tend to increase the rate of decomposition easily. The disadvantages of using agro-waste as optimizers are: they can be messy if not well utilized; end-user may be tempted to use the edible portion of the plant because of its availability; they need time to replenish when over used; they may possess or carry certain diseases that end up contaminating the gas process; they can spread disease if not well used.

Siam weed whose botanical name is “chromolaena odorata" is a tropical species of flowering shrub in the sunflower family (Fig. 2). It is a multi-stemmed shrub that grows tall in open areas. Physically, the plant has a hairy body and gives off a pungent when crushed into a paste. The leaves are opposite, triangular to elliptical with serrated edges. The seeds of this weed are equally hairy because it is a stubborn weed the plant can regenerate from its root and in favourable conditions the plants can grow more than 4 cm per day (Vaisakh and Pandey, 2017).

Fig. 2: Siam Weed

Recently, it has been noticed that the Siam weed has specific healing properties and it has been widely used for agricultural purposes in places like Nigeria. Siam weed contains carcinogenic pyrrolizidine alkaloids. This substance contained in Siam weed is toxic to cattle and could potentially cause allergic reactions to these animals. Recent discoveries show that the plant or weed is parricidal against all major mosquito vectors. The weed is also high in protein as presented in Fig. 3.

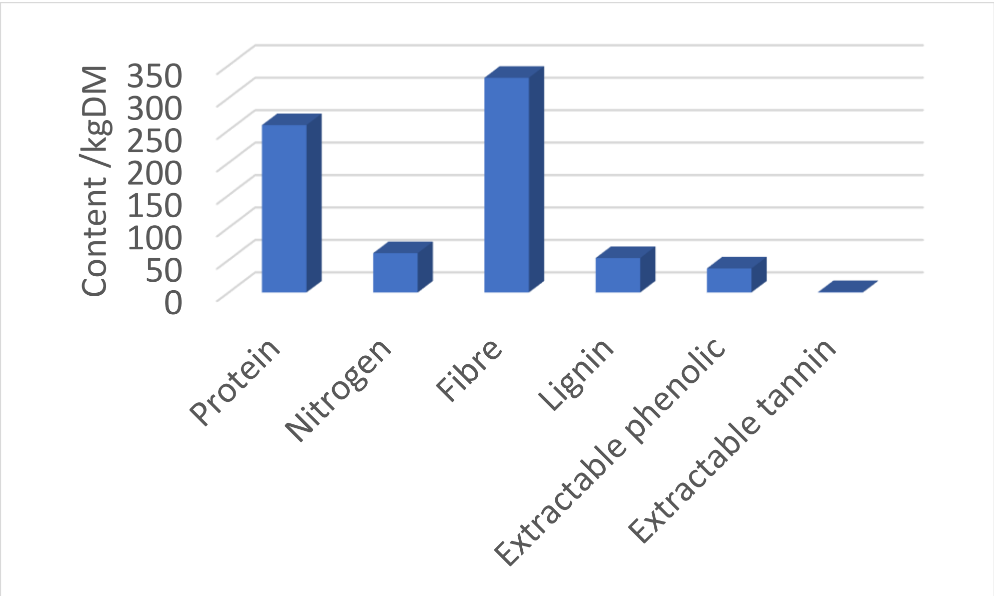


Figure 3: *Element percentage% in Siam weed (Vaisakh & Pandey, 2012)*

The leave is an aid to having an organic matter degradability of 670 /kgDM as estimated by cumulative gas production in vitro after 24 hours of incubation. The second biomass that was used is the plantain peel otherwise known as *Musa Sapientum*. The unripe plantain bark is green in colour and turns bright yellow when ripe (Fig. 4). The banana and plantain come from the same family and are quite similar in looks but they differ greatly in size when ready to use.

In places like Nigeria, the plantain fruit is used to make delicacies such as plantain porridge etc. Sometimes it is dried and blended to a fine powder which is then made into flour or combined with baking. The fruit is said to contain large quantities of iron (Fig. 5). The iron content can be visibly seen when the fruit is cut into, it can also be seen when boiled or heated because the iron turns black or grey and can be seen as the sticky substance at the corners of the pot. The bark is said to contain high quantities of dietary fiber and other metals (Okorie et al., 2015).

Figure 4: African plantain

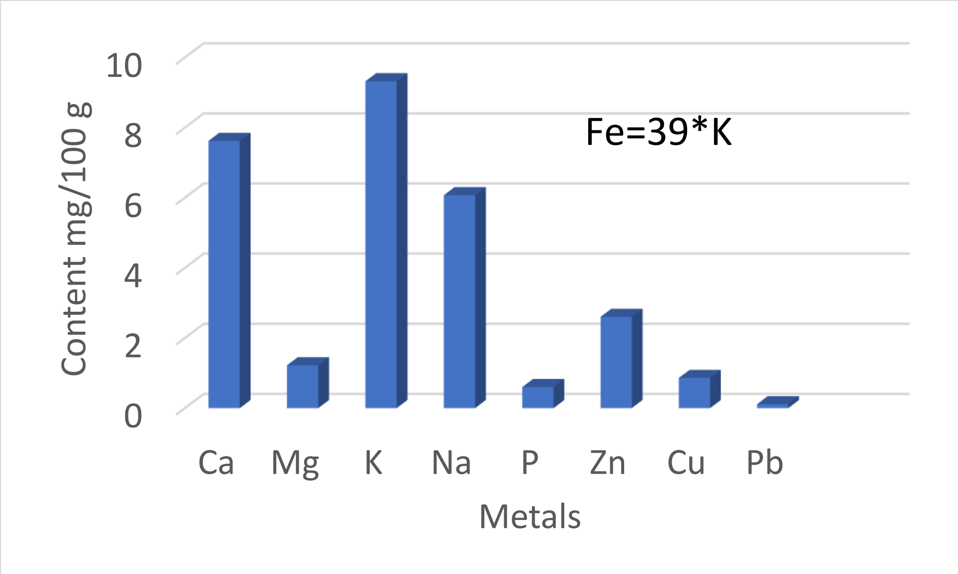


Figure 5: Metal content of plantain peel (Okorie et al., 2015)

The design of the bio-reactor is tailored toward the low cost. The most researched bioreactor is the bio-digester septic tank design (BDSTD) (Fig. 6 and 7). It is easy to construct and can be adapted to the poorest of homes in third-world countries. BDSTD does not emit stench like ordinary septic tanks. It works well for families, schools and hospitals, among others, because it eliminates the risk of spreading diseases. The physics of the bio-digester septic tank design is the diagonal placement of the inlet, overflow, and outlet chambers to enhance maximum contact time with the microorganisms to enable swifter digestion of the sludge. The addition of the microorganism into the septic tank can be controlled by two processes, i.e., oral observation and device monitoring. Oral observation entails that the user observes the quality of combustion of the biogas. The second option is the device monitor to measure the quality of the biogas. Also, there is an enhanced stream flow in vertically placed pipes. The volume of the BDSTD in cubic meters is calculated by multiplying the size of the BDSTD (S_{bdstd}) by the hydraulic retention time (H_{RT}), which is mathematically represented as S_{bdstd} x H_{RT}. The construction i.e., BDSTD-1 presented in Fig. 6 has the first chamber from the toilet, here, the semi-purified water moves to the second chamber via the overflows that are constructed such that the upward movement of water prevents larger particles from flowing into the second chamber. The feeding, digestion, and settlement of organic matter continue in the second chamber. Due to the size variation between the first and second chambers, it is expected that the retention time in the second chamber is less than half of the first chamber. The third chamber, i.e., the outlet receives the overflow from the second chamber. The size of the io-digester septic tank design is hinged on the number of users as it is assumed that the rate of sludge generation in septic tanks is around 0.05 cubic yards every year for an individual. The shape of this type of bio-digester septic tank design (circular or cuboid) depends on land mass management which is at the owners' discretion. However, it is best to simulate the design before the main construction.

The second design i.e., BDSTD-2 is presented in Fig. 7. BDSTD-2 comes with different variations but same principles. The system consists of an inlet that collects sewage from different points and transports it into the soak pit and unto the outlet. BDSTD-1 and BDSTD-2 have the almost same principle. The difference is that BDSTD-2 is not compact and may experience more retention time. The inlet section could also be modernised to separate black and grey water using a grease interceptor. The black water contains the faecal matter while the grey water contains fats, oils, greases, waxes, and detergents, which can make the anaerobic digestion chemically unstable. The black water is then transported into the main chamber, which uses naturally occurring anaerobic bacteria to treat it by digesting the matter while eliminating the disease-causing organisms.

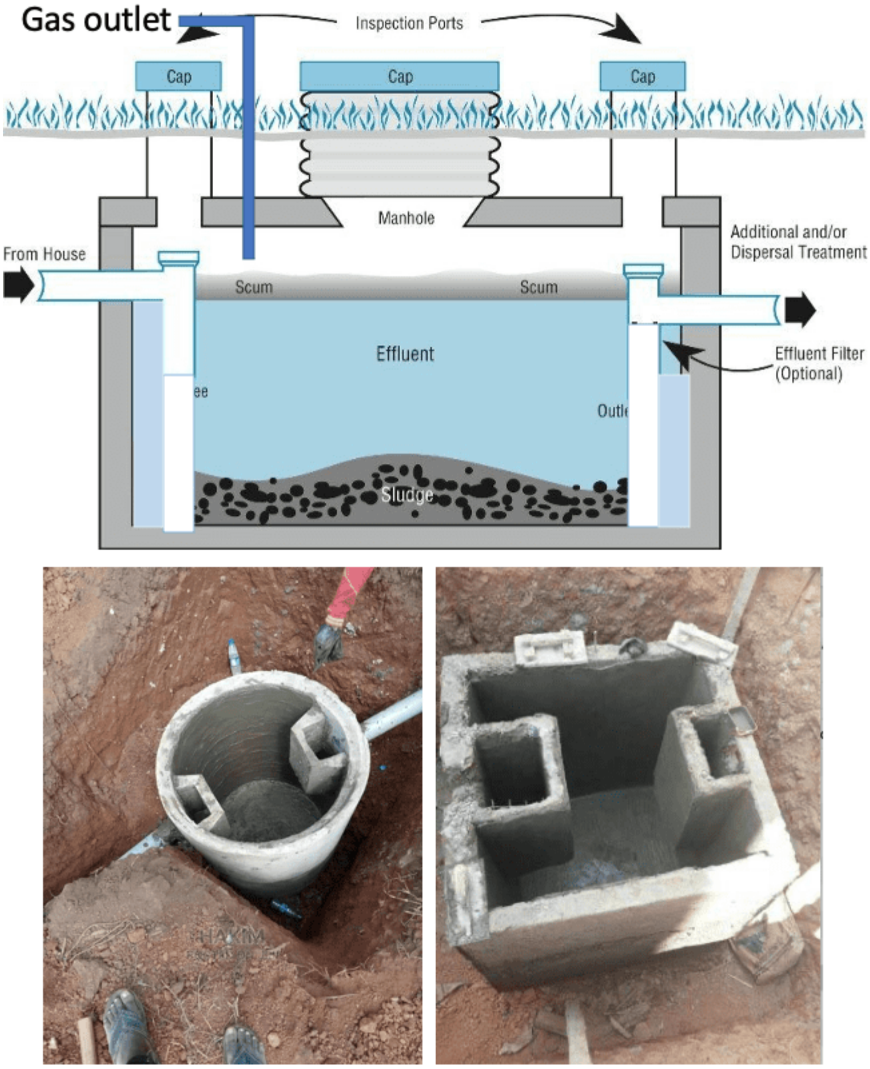


Figure 6: Bio-digester septic tank design (BDSTD 1) (Scott, 2022; Kirumira, 2019;

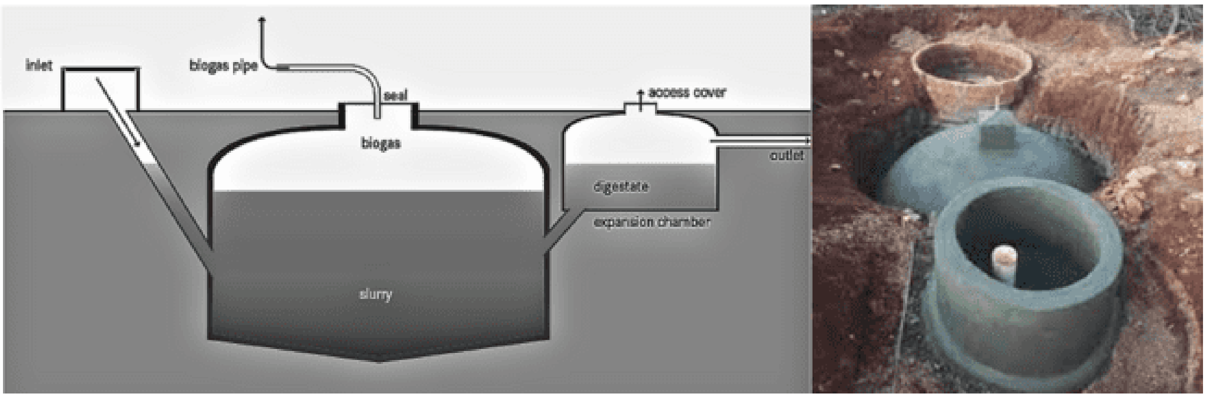


Figure 7: Bio-digester septic tank design (BDSTD 2) (Tilley et al., 2014; Valli, 2020)

The physics of BDSTD-1 and BDSTD-2 can be better represented by a mathematical equation:

$$G = \left\{\frac{1}{y}V_i t_{R1} + \left(\frac{y-2}{y}\right)\left(\frac{V_b V_s t_{R2}}{V_m}\right) - \frac{1}{y}V_o t_{R3}\right\} G_y$$

(1)

Where G is the daily gas production rate (m^3/kg), V_i is the volume of the inlet chamber where biomass is added per day (m^3/day), y is the partition cross-section of BDSTD that shows the sizes of each units, t_{R1} is the retention time in the inlet chamber, V_s is the volume of the biomass added per day in the biodigester chamber (m^3/day) via the cap into the soak pit chamber where the microorganism had begun their growth phases, V_m volume of the microorganisms added per day (m^3/day), V_b is the volume of the biodigester per day (m^3/day), t_{R2} is the retention time in the biodigester, V_o is the volume of the biomass removed from the biodigester per day in the biodigester (m^3/day), t_{R3} is the retention time in the outlet, and G_y is the gas yield per kg of excretal per day (m^3/kg/day).

$$\frac{G}{G_y} = \frac{1}{y}\frac{dV_i}{dy}t_{R1} + \left(\frac{y-2}{y}\right)\frac{d}{dy}\left(\frac{V_b V_s t_{R2}}{V_m}\right) - \frac{1}{y}\frac{dV_o}{dy}t_{R3}$$

$$\frac{G}{G_y}y = \frac{dV_i}{dy}t_{R1} + (y-2)\frac{d}{dy}\left(\frac{V_b V_s t_{R2}}{V_m}\right) - \frac{dV_o}{dy}t_{R3}$$

$V_i = V_o$; $V_b = 10V_o = 10V_i$; $3V_b = V_s$

$$\frac{G}{G_y}10y = \frac{dV_b}{dy}t_{R1} + 30(y-2)\frac{d}{dy}\left(\frac{{V_b}^2 t_{R2}}{V_m}\right) - \frac{dV_b}{dy}t_{R3}$$

$$\frac{G}{G_y}10y = \frac{dV_b}{dy}\left(t_{R1} + 30(y-2)\left(\frac{V_b t_{R2}}{V_m}\right) - t_{R3}\right)$$

(2)

The significance of equation in practical terms is a model to help the BDSTD designer to estimate other germane processes (such as expected gas yield and volumetric estimation of biogas production within the facility) that cannot be simulated on a construction simulator.

Four steps were used in this section to accomplish the set objectives of this research. The methods are preparation of materials; laboratory set-up of the gas production; data generation and analysis; and modelling. The Siam leaves were harvested, washed to remove dust and other deposits, and blended using an electric blender into an aqueous paste. The aqueous paste was placed in a container. The African plantain was purchased as unripe. The plantain peel was also washed to remove unknown deposits and was blended into an aqueous paste.

The laboratory scale biodigester was constructed as described in Emetere et al. (2022). Three set-ups were established, i.e., pure faecal matter set-up (TF), faecal matter and Siam leaves set-up (SF), and faecal matter and plantain peel set-up (PF). The mixing ratio of faecal matter to water was 3:1 for all set-ups. The container was shaken to make the faecal matter into a slurry. In PF, 1.054 kg of plantain peel aqueous paste was mixed with 5.27 kg of slurry. The mixture was vigorously shaken to obtain a fairly homogenous compound. In the SF set-up, 0.876 kg of the Siam leaves aqueous paste was mixed with 4.38 kg of slurry. Also, the mixture was vigorously shaken to obtain a fairly homogenous mixture. The quantity of feedstock plays a significant role in determining the magnitude of biogas production. This research concentrates on the trends as it is an important factor that would be needed for live application. In general, the mixing ratio of agro-waste to faecal matter should be about 1:5 as already explained by Emetere et al. (2022). In the TF set-up, the slurry used was 2.325 kg. Four parameters were measured during this experiment, i.e., the ambient temperature in the laboratory, the mass of the biogas that is trapped within the balloon/bladder, the bacteria growth as seen in the increase of the digestate mass, and the time which was measured in twenty days. The ambient temperature was obtained using via thermal reading around data collection point. The masses of the digestate and biogas were measured using digital weighing balance. The time was measured using the digital watch.

The daily biogas yield was logged onto an excel sheet where the necessary conversion was made before estimating daily gas production. The MATLAB software was used to analyse, project production (using machine learning) and model a life scenario using the Bio-digester septic tank design (BDSTD) described in the previous section.

6. Results and Discussion

The biogas discharge and daily gas production rate within the twenty days are presented in Fig. 8. The biogas discharge was first measured by weighing the gas bladder for each day (Fig. 8a). It was observed that biogas from plantain-faecal (PF) had the highest cumulative production within the experiment while the biogas from Siam-faecal (SF) had the lowest. This result shows that the plantain biomass may aid initial bio digestion of the faecal samples due to its inherent chemical components which are important to breaking undigested food components in the faecal mass. Siam biomass seems to have the opposite functionality as its component cannot easily break undigested food components in the faecal mass. It was found that the pure/total faecal (TF) sample discharges more biogas than the SF.

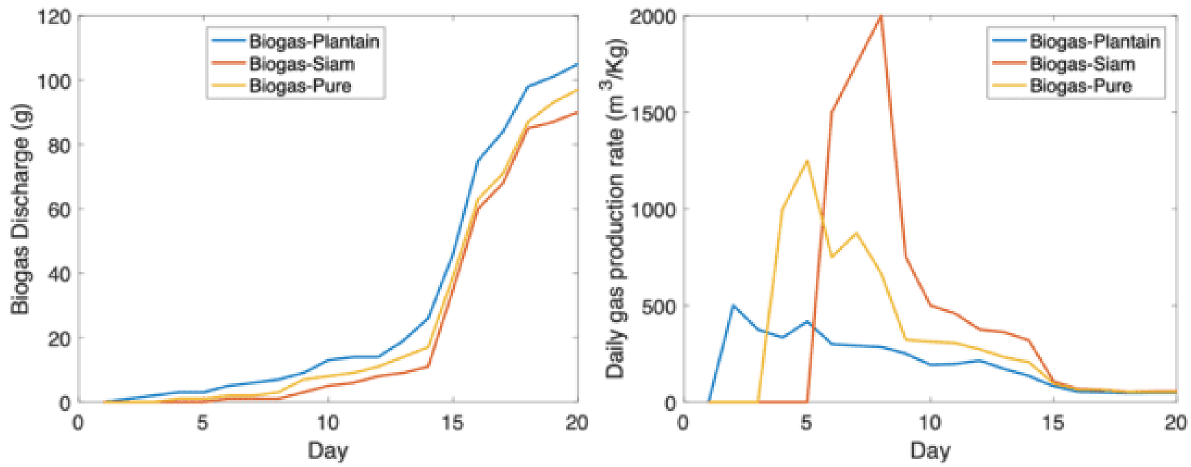


Figure 8: Biogas production (a) biogas discharge (b) daily gas production rate

Fig. 8a reveals the interplay of microbial colonization in bio-digestion of faecal samples to generate biogas. The daily gas production rate shows that PF ability to break undigested foods aids microbial activities initially but may not create an enabling environment for the rapid growth of the biogas-aiding microbial. Also, the difference of the feedstock has slight significance on the biogas discharge and daily gas production rate of PF. The daily gas production rate in SF shows that when the initial breaking down of undigested food in the faecal occurs, it supports microbial growth that would lead to 400 % biogas generation over PF and 160 % biogas generation over TF. However, the bottleneck of the daily gas production rate in SF is the level of breaking of the faecal samples. The Machine Learning method was used to investigate the scenario for both biogas discharge and daily gas production rate for thirty days as presented in Fig. 9

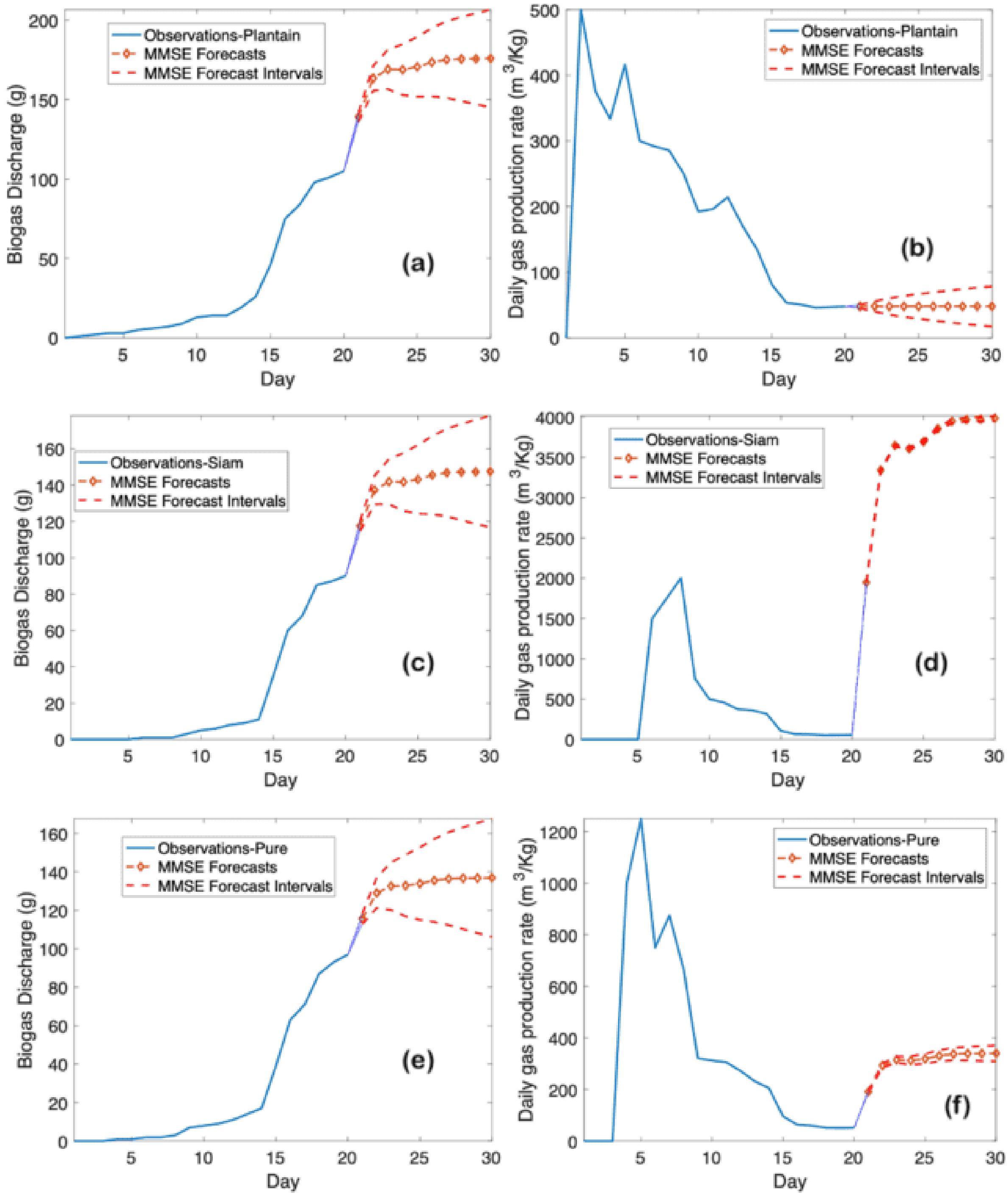


Figure 9: Machine learning predictions (a) PF biogas discharge (b) PF daily gas production rate (c) SF biogas discharge (d) SF daily gas production rate (e) TF biogas discharge (f) TF daily gas production rate

The Minimum Mean Square Error (MMSE) forecast estimator was adapted for the study. MMSE is an estimation method that minimises the mean square error (MSE) of the fitted values of a dependent variable. In practical terms, MMSE is used to analyze the estimator quality. Fig. 9a shows the computational forecast of PF biogas discharge which is expected to increase maximally and minimally by almost 100 % and 50 % respectively between 20 and 30 days. Likewise, the daily gas production rate of the PF is slightly going to increase maximally and minimally by almost 20 % and 5 % respectively between 20 and 30 days (Fig. 9b). In practical term, as the faecal mass increase due to human daily input into the BDSTD, the already produce microbes in the chamber would start acting on the new feedstock to give faster biogas generation. The protocol is not expected to decrease as long as human activities do not seize. In other words, plantain biomass is recommended for bigger BDSTD for schools, worship centers, markets, and workplaces. Fig. 9c shows that the forecast of SF biogas discharge is expected to increase maximally and minimally by almost 80 % and 10 % respectively between 20 and 30 days. This outcome is almost the same as seen for the scenario in TF (Fig. 9e). The daily gas production rate of the SF was shown to increase maximally and minimally by almost 200 % and 180 % respectively between 20 and 30 days (Fig. 9d). This result further confirms the observation earlier established that the more the undigested food in the human faecal sample increase, the more microbial growth increase to see commensurate biogas generation. This result is quite different from TF's daily gas production rate, which slightly increased by 20 % (Fig. 9f). In practical terms, Siam biomass is recommended for domestic homes for maximum and sustainable biogas production. The recommendations are based on the volume of feedstock generated by the specific users and the production trends initiated by the agro-waste.

The quality of the biogas produced in the PF, SF, and TF is presented in Table 1. The concentration of the CO_2 gas is direct evidence of microbial growth in both PF and SF. There was growth in TF also, but the GC-MS used gave the outcome for selected gases as presented in Table 1. The decrease in oxygen and increase in CO_2 further proves the population of microbes as they have been reported to convert dissolved oxygen to carbon dioxide (Robinson, 2019). The high CO content as seen in PF and SF could be further oxidized using bacteria such as carboxydotrophs, methanotrophs, dinitrogen-fixers, acetogens, methanogens, and phototrophs (Meyer & Fiebig, 1985; Cordero et al., 2019). Furthermore, enzymes containing metals such as molybdenum or nickel are a better candidate for oxidizing CO content. Also, there is evidence of nitrate respiration by some of the initial microbial in both PF and SF which are expected to lead to denitrification and anaerobic ammonium oxidation (Kraft et al., 2011). Since biogas is usually made up of around 50-70% methane (CH_4) and 25-45% carbon dioxide (CO_2), with other gases such as hydrogen (H_2), hydrogen sulphide (H_2S), water vapor (H_2O), nitrogen (N_2), oxygen (O_2), ammonia (NH3) and sulphur dioxide (SO_2), the prospects of further reactions to meet-up with biogas quality and quantity (as shown in Table 1) is visible as already proven by researchers (Manjappa, 2014; Dahunsi et al. 2018; Devi et al., 2022).

Table 1: Component of biogas

Element	**PF (ppm)**	**SF (ppm)**	**TF (ppm)**
O2	3.6	3	0.45
CO	1099	1199	N/A
CO2	1.5	7.8	2.63
NO	13	8.1	N/A
NO2	6.7	13	59.09
SO2	2.3	0	N/A
CH4	48.9	14.7	38.23
H2S	6	2	N/A

The theoretical investigation into the BDSTD design is displayed in Fig. 10 as simulated from equation 2. Technically, the partitioning cross-section of the BDSTD as seen in Fig. 6 & 7 plays a vital role in the ease of harvesting the biogas as soon as it is produced. The implication of the partitioning is shown in the figure, which had nine partitions with one portion as an inlet chamber, seven portions as an overflow chamber, and one as an outlet chamber. The assumption in this design is that the depth of the BDSTD is the same. The second assumption is that the inlet and outlet chamber should be a portion each within the cross-sectional partitions. Fig. 10a reveals a scenario where the partitioning cross section is four. In this type of design, it is projected that if all conditions as earlier explained in the laboratory experimentation remain the same, an average of 885 m^3/day volume of biogas can be extracted per day. Also, the flow of faecal mass across the chambers and the biogas generation are equally commensurate. Hence, plantain biomass is recommended for this design as there would be a shorter time in the overflow chamber. Fig. 10 b-d show that higher cross-sectional partitions would lead to lower biogas production with a higher retention time in the overflow chamber. In this case, the Siam biomass is recommended. At higher cross-sectional partitions (Fig. 11), it is projected that the fluid transport of the biogas within the overflow chamber could imply sustainable biogas generation as it will now depend on the prevailing weather and how it influences biogas production.

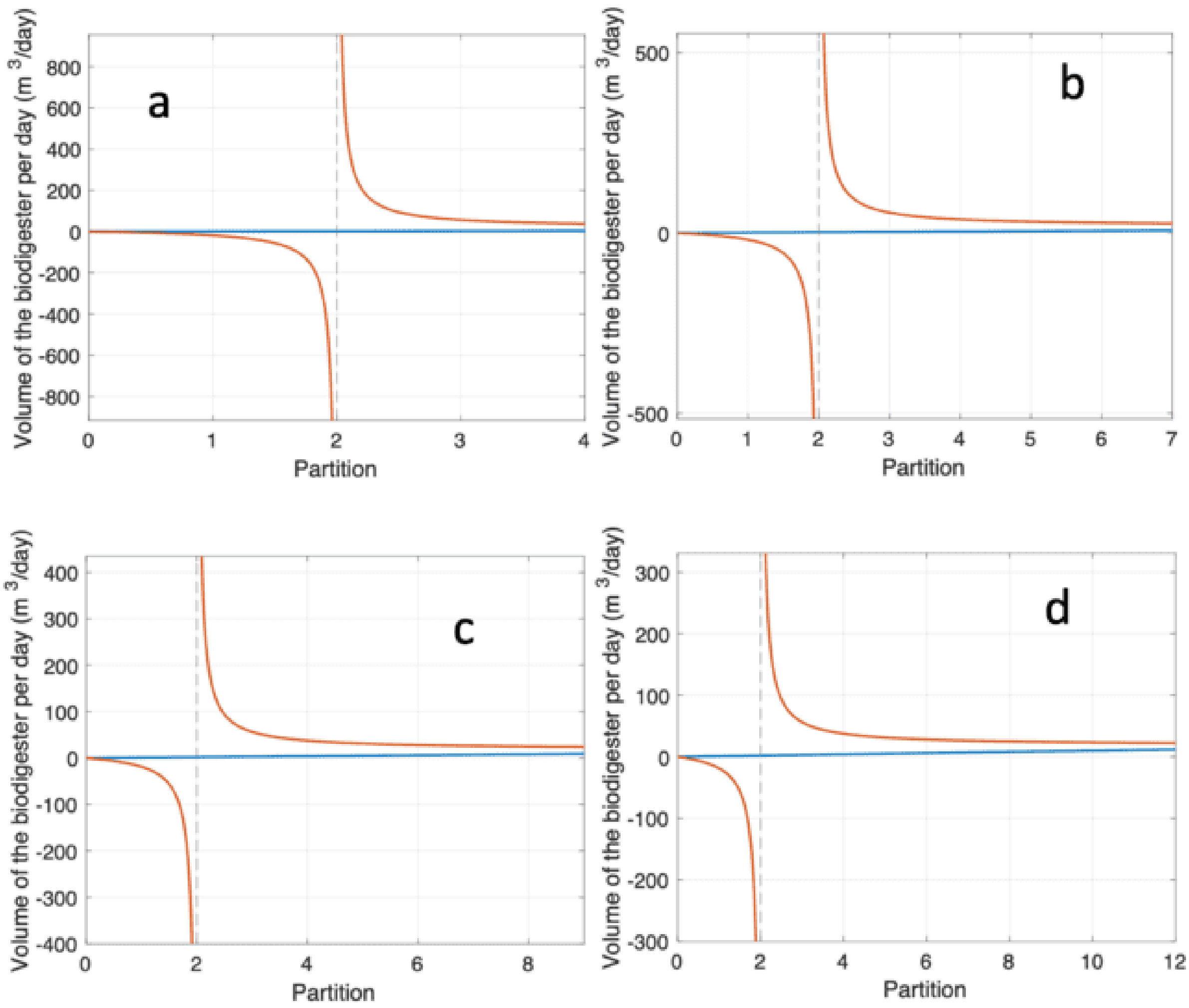


Figure 10: Theoretical investigation of BDSTD design

Overflow chamber	Overflow chamber	Overflow chamber
Inlet chamber	Overflow chamber	Outlet chamber
Overflow chamber	Overflow chamber	Overflow chamber

Figure 11: Theory of cross-sectional partitioning

Conclusion

At the end of this research, it was proven that agro-based biomasses are a vital catalyst for optimizing human biogas from human waste. The agro-based products used in this project were performed according to their inert components or elements. They are also influenced by other factors such as feedstock mixing ratios, number of days, temperature etc. Biogas from plantain-faecal (PF) had higher cumulative production than biogas from Siam-faecal (SF) because plantain biomass aids initial bio-digestion of the faecal samples due to its inherent chemical components which are important to breaking undigested food component in the faecal mass. In this wise, the chemical component in Siam biomass cannot easily break undigested food components in the faecal mass. However, SF creates a better enabling environment for microbial growth that could lead to about 400% biogas generation over PF and 160% biogas generation over TF. Despite this feat, the caveat for improved daily gas production rate in SF is hinged on pre-processing of the faecal mass. With the aid of machine learning, it was revealed that higher retention time could be a natural way of pre-processing needed by the Siam biomass. This concept led to the design of the BDSTD, which was technically hinged on cross-sectional partitions. It was generally shown that higher cross-sectional partitions would lead to lower biogas production with a higher retention time in the overflow chamber. However, due to weather, each design had its advantage and disadvantages. Plantain biomass is recommended for four partitions BDSTD design as there would be shorter retention time in the overflow chamber, while the Siam biomass is recommended for >4 partitions BDSTD designs. It is recommended that more in-depth research on the chemical properties of Siam and plantain barks of different species be carried-out to guide future user. Also, the anaerobic stability due to continuous microbial addition is recommended for further research.

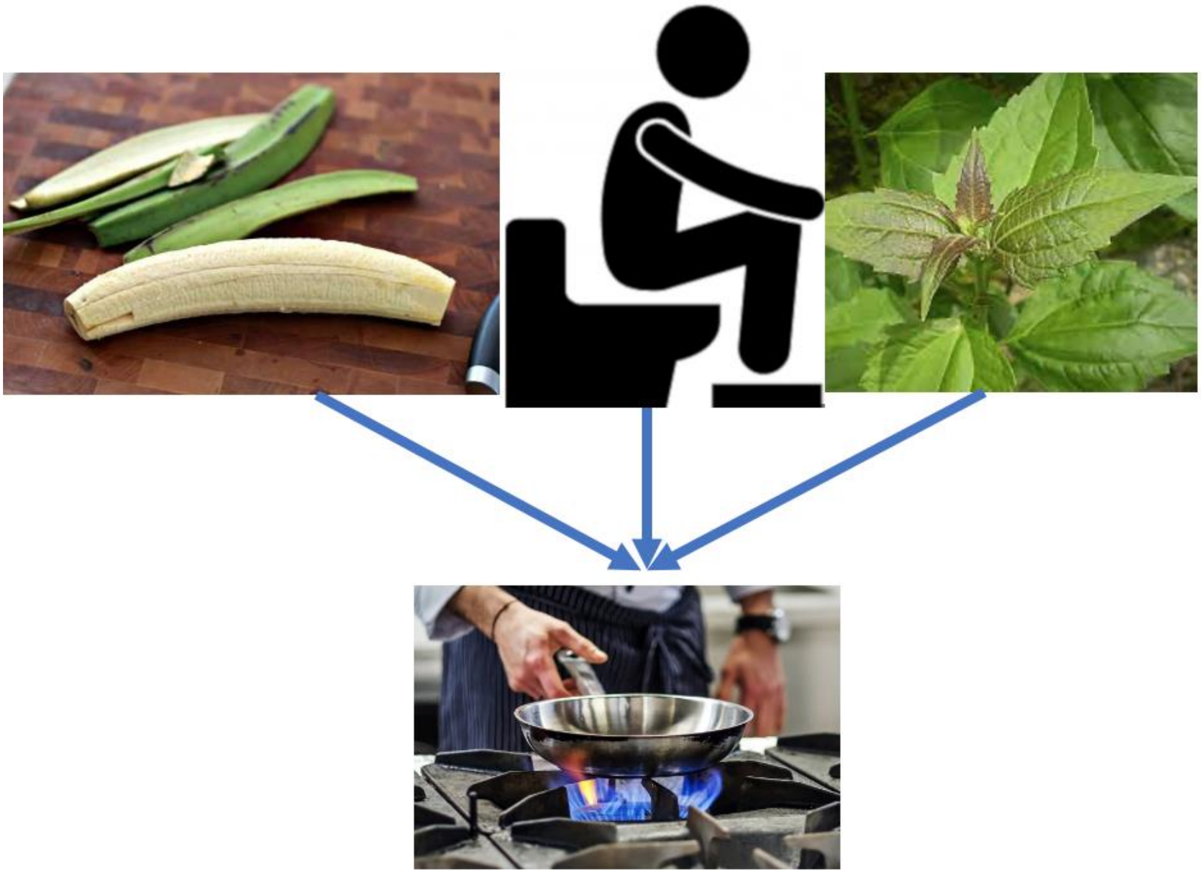
Conflict of Interest

The authors declare no conflict of interest

Novelty Statement

This research paper is the first detailed work on feedstock from human waste and agro waste (Siam leaves and plantain bark)

Graphical Abstract



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