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Faculty of Tropical AgriSciences

Decomposition Processes of Household Waste via Small Scale Biogas Technology:

A Case Study of Nigeria

MASTER'S THESIS

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Author: Olumba Genevieve Chinwe

Chief supervisor: doc. Ing. Hynek Roubík, Ph.D.

DECLARATION

I hereby declare that I have done this thesis entitled Decomposition processes of household waste in small scale biogas technology, a case study of Nigeria; independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague
April 20, 2024
Olumba Genevieve Chinwe

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ABSTRACT

The experiment was carried out to assess decomposition processes of household waste in small scale biogas technology, a case study of Nigeria. Waste samples were collected from three locations (metropolis, satellite and outskirt) of Abuja. Bulked waste samples was put inside a polythene bag and taken to the laboratory for determination of chemical properties according to standard method. Data collected was subjected to Analysis of Variance (ANOVA) and treatments mean were separated using Least Significant Difference (LSD) at probability of 5%. The Results of chemical properties indicated that Soil pH differed in both before and after anaerobic digestion of wastes from the three locations (7.18-7.45), available P content was (0.5 and 0.7mg/kg). Exchangeable bases like K was 51 and 52 respectively. Organic carbon was (30.4and 34.4%), and total Nitrogen (1.2465and 1.45%) while the volume of biogas produced were 24.1g in satellite, 24.0g in outskirt and 22.0g in metropolis respectively. Cumulative biogas yield at 21 days after the setup of anaerobic digesters with 180 second of time of cooking period with a production of 73.33g, 23days of 360 seconds of cooking period with a production of biogas 133.33g, 25days of 270 seconds of cooking period with a production of 93.33g and 30 days of 90 seconds of cooking period with the production of 63.33g of biogas. However, there were all significantly different at 5% level of probability. Chemical properties analysis were compared with soil fertility ratings. Soil pH was slightly alkaline, organic carbon, total nitrogen, total exchangeable base like potassium were high while available phosphorus was low. The volume of biogas generated by anaerobic digester containing wastes from satellite location of Abuja produced the highest volume of biogas followed by outskirt and metropolis respectively. It was also observed that the volume of biogas production declined along days of setup. Therefore, further studies should be conducted to produce biogas using household waste in commercial quantity.

Key words: Biogas Technology, Household Waste, Anaerobic Digestion, Chemical properties, Nigeria

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AD- Anaerobic Digestion

LPG- liquid petroleum gas

OLR- Organic loading rate

C/N- Carbon-nitrogen ratio

VFA- Volatile Fatty Acids

DM- Dry Matter

VS - Volatile Solid

FCT- Federal Capital Territory

VSR- Volatile solid removal

1.0 INTRODUCTION

The development of renewable energy is one of the well-researched topics worldwide. It has gained worldwide attention, with thousands of articles published annually that provide new strategies and technologies to support the improvement of clean energy. Additionally, the growth of the world's population currently stands between 1% and 2% annually (Xu *et al.*, 2018), and is expected to increase to more than 9 billion by 2050 (Srisowmeya *et al.*, 2020) with an increase in industrial activity expected to lead to growth in a wide range of waste products, such as industrial waste, municipal solid waste and animal waste (manure). Food waste, as the main component of municipal solid waste, has recently experienced rapid growth due to population growth, which has also accelerated the construction and competition of numerous food restaurants. Globally, approximately 1.3 to 1.6 billion tons of food waste (FW) are generated every year (Gallipoli *et al.*, 2020). In fact, to reduce the enormous volume of waste, countries face a significant challenge in finding the appropriate management tools to dispose of waste safely. Generally, conventional disposal methods, including landfill, open dumping, and burning, are still applied by most countries to treat most of the waste produced (Caicedo-Concha *et al.*, 2019). Furthermore, the demand for available land outside cities continues to increase, despite environmental damage from greenhouse gas emissions and other harmful toxic effects (Kumar and Samadder, 2020). Composting is considered one of the treatment processes used to efficiently recycle food waste. It improves soil health and reduces environmental risks (Kim *et al.*, 2020) but it also requires a large treatment surface. On the other hand, with the continuous increase in energy requirements, many of the FW treatment practices are utilized to recover clean energy, reduce waste volume and maintain environmental protection. For this reason, thermal treatment processes are applied as alternative waste disposal techniques (Zhang *et al.*, 2018)]. An environmentally friendly process can extract energy located in FW as biogas (Atelge *et al.*, 2020) and exploit the residue to produce bio-fertilizer (Ma et al., 2018). Anaerobic digestion is the appropriate operation that can combine sustainable energy production presented by biogas (Ekanthalu *et al.*, 2020) that generates heat and electricity and recovers nutrient-rich digestate in the form of biofertilizer (Masebinu *et al.*, 2019).

AD operation is a complex and sensitive process, and requires adequate control and monitoring. It is a biological process that is affected by environmental factors such as temperature and pH. In addition, it can be inhibited by the accumulation of ammonia and VFA during the process, leading to the problem of low methane yield. Furthermore, the carbon-to-nitrogen ratio (C/N), the moisture or total solid content (TS), the volatile solid (VS), and the organic loading rate (OLR) are the operational feedstock parameters. They also play a significant role in either the enhancement of the process or its termination. Furthermore, mathematical modelling of the AD process is key to estimating the amount of biogas production (Gallipoli *et al.,* 2020; Li and Wang, 2017), the concentration of VFA (Wang and Li, 2019), and other continents. In this research, we provide a comprehensive review of the AD process, including attractive issues concerning this process. We explore the impact of the various factors influencing the anaerobic digestion process, focusing on the mathematical models developed by the scientific community and presenting their advantages and limitations.

Everything, in essence, is about energy. There is no doubt that energy is fundamental to our development. Energy is vital for the internal and external security of a country, and energy issues are at the core of social, environmental, and economic security challenges. The world is experiencing an economic downturn and in these dire times, individuals and institutions are more likely to consider options for renewable energy or other measures that help the environment. As the demand for fossil fuels in the world increases and with their price increase, interest has deservedly begun to be given to the development of renewable energy sources. The search for energy alternatives involving locally available renewable resources is one of the main concerns of governments, scientists and business people worldwide (Deublin and Steinhauser, 2008). Biogas is defined as a combustible mixture of gases produced by microorganisms when biological wastes are allowed to ferment in the absence of air in closed container (Giampietro, 2008). Biogas is mainly composed of 50 to 70 percent methane (CH_4), 30 to 40 percent carbon dioxide (CO_2) and low amount of other gases. Biogas is about 20 % lighter than air and has an ignition temperature in the range of 6500C to 7500C.

It is odourless and colourless gas that burns with clear blue flame similar to that of liquid petroleum (LPG) gas. Its caloric value is 20 Mega Joules (MJ) /m3and burns with 60

%efficiency in a conventional biogas stove. Biogas refers to a gas made from anaerobic digestion of agricultural and animal waste (Drapcho *et al.,* 2008). Gas is useful as a fuel substitute for firewood, dung, agricultural residues, petrol, diesel, and electricity, depending on the nature of the task and local supply conditions (James and James, 2012).

1.1. Justification

Today, organic waste and especially household waste represent a significant global issue due to population growth. The anaerobic digestion (AD) process is an essential operation that contributes powerfully to the valorisation of organic waste including food waste in terms of renewable energy generation (biogas) and the rich- nutrient residue that can be utilized as bio fertilizer. Thus, this process (AD) allows for a good recovery of household waste by generating biogas and compost. However, AD operation has been affected by several key factors. In this project, I aim to involve different critical parameters that influence the AD process, including temperature, pH, organic loading rate (OLR), carbon to nitrogen ratio (C / N) and total solid content (TS(%)). Furthermore, the research will highlight the inhibition caused by the excessive accumulation of volatile fatty acids (VFA) and ammoniac, which exhibits the positive effects of co-digestion, pre-treatment methods, and mixing techniques for maintaining process stability and enhancing biogas production. I will analyse some current mathematical models explored in the literature, such as distinct generic, non-structural, combined, and kinetic first-order models. Finally, the study will discuss challenges, provides some possible solutions, and a future perspective that promise to be a highly useful resource for researchers working in the field of large household waste recovery for the generation of biogas.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Biogas Technology

2.1.1 Standard design systems

Biogas is a sustainable and affordable technology for rural areas where it is more convenient to adopt cheaper and simpler anaerobic systems to benefit from biogas production (Woldeyohannes*et al.,* 2016). Household digesters are inexpensive, easy to operate and maintain, and often constructed using local materials. The selection of biogas systems depends on the construction, design skill, and material availability. Furthermore, the design depends on the type of feedstock, climatic conditions, and geographic location. Generally, those systems do not have controlinstruments and heating apparatus and serve at room temperature (psychrophilic or mesophilic temperature) (Teodorita *et al.,* 2008). In tropical countries, digesters are underground to take advantage of geothermal energy; meanwhile, in mountainous regions, systems have a reduced amount of gas to avoid discrepancies between hot and cold season biogas production (Rajendran *et al.,* 2012). Traditionally, biogas generated is used for cooking and lighting; however, biogas for electricity is increasing (Ciotola *et al.*, 2011).

The most diffused systems in developing countries are fixed dome, floating drum, and plug flow type. The fixed dome model is also called the hydraulic digester (Figure 1) developed in China, where more than 45 million systems have been installed (Bond and Templeton, 2011); this type of system is also implemented in South Asia and Africa (Ghimire, 2013). Typically, it consists ofan underground digester and a dome-shaped roof. The size of the digester depends on the amountof substrate available and the location; Biodigesters are typically 6 to 8 m3 and operate in a semi-continuous mode. The new substrate is added once a day, while an equal amount of decanted mixed liquid is removed (Teodorita *et al.*, 2008). The digester is built from bricks, cement and reinforced by concrete. The system has one central part, the digester, dedicated to fermentation and located at a deeper level; above the ground level, there are two rectangular openings on each side, which act as the input and outlet points for the digester. At the top of the dome-shaped roof, there is a pipe that is the biogas outlet. The digester is filled through the inlet, while the outlet also plays the role of the hydraulic chamber. During the process, biogas is produced in the digester and fills the upper part called the storage part (i.e., the dome). The pressure generated by the biogas presses the slurry from the digester into the inlet and outlet tanks. When the gas is released, the slurry flows back into the digester. Over the decades, this model has been improved and new designs have been developed. In China, digesters were modified with a hemispherical shape with a wall in the middle to increase retention time and ensure a complete digestion process. Different fixed dome models were developed in India; first, the Janta model, a shallow system with a dome roof, has an inlet and an outlet above the dome equipped with a gas pipe. The Deenbandhu model, which is a modification of the Janta model, consists of two spheres; at the bottom, there is the fermentation unit, while at the top, there is the storage unit. In India, a low-cost model for light purposes was also designed with a vertical cylinder as a dome and with long inlet and outlet tubes (Jash and Basu, 1999). In Pakistan, French-model digesters were installed; in this case, the digester is surrounded by a steel dome to prevent loss in temperature (Nazir, 1991). In recent years, alternative construction materials havebeen introduced to reduce labour costs and increase the life of the system. Polymers and glass fibre reinforced plastics are used today (Deng *et al.*, 2017). The fixed dome design is a reliable model with low maintenance and a long lifetime; for these reasons, it was widely implemented (Ghimire, 2013

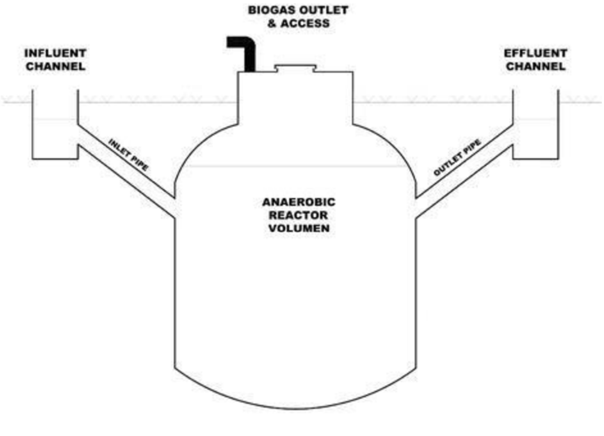

Figure 1. Scheme of the fixed dome digester model (Lohri et al., 2013).

India developed the floating drum model (Figure 2); its design comprises a mobile inverted drumplaced on the block digester with inlet and outlet connections through pipes located at thebottom. The digester is often partially underground. The drum acts as a reservoir; it can rise and fall along a guide pipe, depending on the volume of biogas produced. It produces biogas at constant pressure with variable volume. The weight of the drum applies the pressure required for the gas to flow through the pipeline. The digester is generally made of bricks and concrete. Meanwhile, the drum is made of metal or steel and coated with paints or bitumen to avoid corrosion, determining its lifespan. Galvanized metal and fiberglass-reinforced plastics represent a suitable alternative to standard steel (Rajendran *et al.*, 2012).

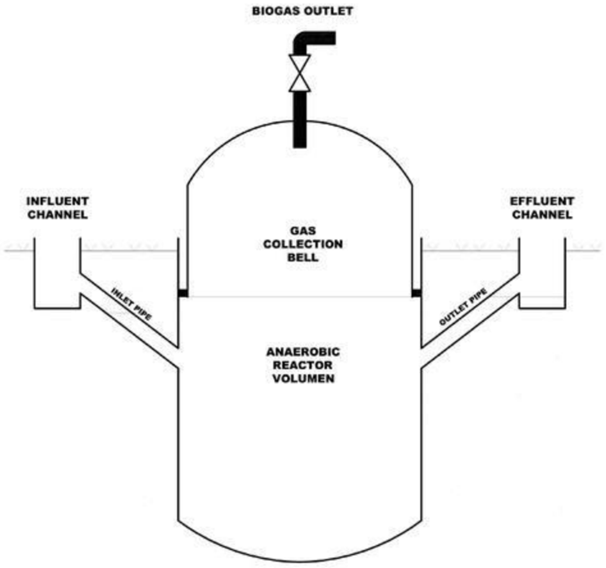

Figure 2. Scheme of the floating drum digester model (Lohri et al., 2013).

The plug flow type or tubular model (Figure 3) was developed as a portable model. This model iswidespread, especially in South America (Garfí *et al.*, 2016). It comprises a narrow and long tank (length: width equal to 5:1) inclined and partially buried in the ground, with the inlet and outlet over the ground and on the opposite side. Due to the inclination, the digestate flows toward the outlet; it is a two-phase system where acidogenesis and methanogenesis can be separated longitudinally. To keep the process temperature adequate, the system needs insulation and, generally, a shed roof is placed on top of the digester (Rajendran *et al.*, 2012).

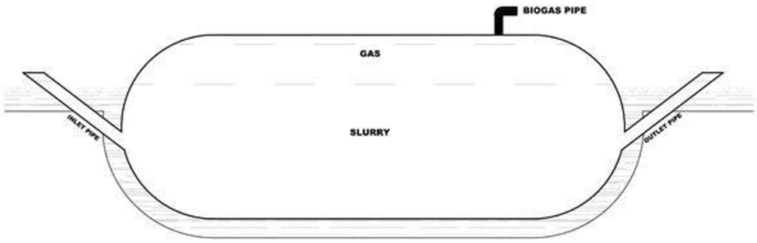

Figure 3. Scheme of the tubular digester model (Lohri et al., 2013).

When comparing the tubular digester model with the fixed one, the fixed model can be fed with manure ratio: water 1:1, while tubular model 1:3, the former needs three times the amount of liquid (Martí-Herrero, et al., 2014). Compared to the fixed dome, the plastic tubular digester has several advantages. It is a very low-cost model suitable for high altitude and low temperature, it is easy to transport and simple to install with lower investment costs, it requires less maintenance and is more environmentally friendly (Garfí et al., 2014). If hard-constructed models are compared from an economic point of view, for a capacity of 1 to 6 m3, the installation cost and the annual operational costs are the highest for the floating model followed by fixed ones (i.e., Janta and Deenbandhu models). The floating type also has a longer payback period. With increasing capacity, the cost of installation and the annual operational costs increase proportionally and the payback period increases. The Deenbandhu model (capacities from 1 to 6 m3) was shown to be the cheapest model (Singh and Sooch, 2004). Scheme prefabricated and low-cost digester (GTZ 2015) provides an excellent example of such cost-effective options (figure 4).

Regardless of the model, household biogas systems may include auxiliary equipment to mix and handle slurry and gas. Gas equipment can comprise pipes, valves, and manometers (Vögeli et al., 2014).

Local conditions, biogas users’ needs, waste, water, and land availability are the criteria used to select the appropriate digester design in terms of volume and building materials (Ferrer-Martí *et al.*, 2018). Together with the different operational parameters, the design determines the biogas production and the quality of the digestate. As a decentralized energy resource, poor design represents a particular limitation to user adoption (Yaqoot *et al.*, 2016). Furthermore, the size of the digesters according to local needs and the reduction of the discrepancy between demand/production can avoid the excessive production of biogas that often drives users to leak itinto the surrounding environment deliberately, and this causes a negative environmental impact (Ioannou-Ttofa *et al.*, 2021).

Figure 4. Scheme prefabricated and low-cost digester (GTZ 2015)

Table 1. Principal household designs used in developing countries (authors adaptation from literature sources).

Type of design	Fixed dome digester		Floatin g drum digester	Tabula R
Modifications /models	Janta Deenbandhu French			Tubular Pre- built and low-cost digester
Construction/Fabrication Materials	Bricks Cement Concrete Polymers Glass-fiber-reinforced plastics		Bricks and concrete for digester Metal or Mild steel for drum Reinforced fiber plastics high-density polyethylene (HDPE)	PE PVC HDPE Glass fiber reinforced plastics
Advantages	Low initial cost long-life span (if appropriately built) Less land required		Easy construction Visible storage volume Visible storage volume	Low cost, Easy transportation, Easy installation, Low maintenance
Disadvantag es	Requires high construction skills	Built with heavy materials Gas leakage due to cracks	High installation and operational costs High payback. Short life span (corrosion of drum) High maintenance	Short life, Span Requires insulation in a cold climate Requires a high amount of water Low gas pressure
Geographical Diffussion	China India Nepal Uganda Tanzania		India	South America Africa South Asia

Sources	(Arelli et al., 2018)	(Arias et al., 2021)	(Bansal et al., 2017)	[39]

2.1.2 Prefabricated and low-cost digesters

In recent years, pre-fabricated systems were preferred for projects involving rural communities in developing countries. These systems are also called 'commercialized digesters' and are often called 'news digesters' because they involve new production materials, processes and techniques. The main models commonly used in developing countries are composite material digesters and bag digesters (Cheng *et al.*, 2014).

The bag digester is also called a balloon digester or tube digester, and has a sealed soft plastic tubular structure. The long cylinder is generally made of polyvinyl chloride (PVC), polyethylene (PE) Scheme Prefabricated and low-cost digesters, or rubber. It was developed to address construction problems with solid digesters (fixed and floating models). Some authors consider the bag digesters and plug flow digesters different types, but in fact, they are similar. In such a system, biogas production is between 0.1 and 0.32 m^3 biogas/ m3 digester / day, which is equal to the yield of traditional digesters used in India (Lansing *et al.*, 2008). The bag digester is more suitable in rural areas where the day temperature is above 20 ° C. This system has been widely applied in South and Central America (Garfí *et al.*, 2011), and at least 1 million low-cost PE plastics were installed in Vietnam with the Ministry of Agriculture and Rural Development. This system requires only two people for installation and can be easily transported, and for this reason, it was widely adopted for remote areas (Cheng *et al.*, 2014).

2.1.3 Influencing parameters

The process of anaerobic digestion requires the right conditions to have adequate biogas production; the parameters that influence the most are temperature, organic waste composition, moisture content, mixing, and hydraulic retention time (HRT) (Sommer, 2007). The generally suitable substrates for biogas production in rural areas are agricultural and livestock residues, organic fraction of solid domestic waste, and domestic sewage sludge (i.e., human excrementand wastewater). The biogas yield depends on the quality, amount, and supply rate (continuous or semi-continuous) of the feed materials. Biogas production can be measured directly bycalculating the pressure of each digestor headspace (El-Mashad and Zhang, 2010). Several parameters can be used for monitoring the value of feedstocks, such as the dry matter (DM), the carbon-to-nitrogen ratio (C:N), total solids (TS) and volatile solids (VS). In general, animal manure is an ideal feedstock due to its high content of moisture and volatile solids (VS) and its buffering capacity, as well as for its variety of microbial strains. The animal manures used in anaerobic digestion may vary according to the geographical area and local livestock practices (Teodorita *et al.*, 2008; Vasco-Correa *et al.*, 2018, Rajendran *et al.*, 2012).

HRT always depends on the temperature and substrate; however, there are no regulatory instruments and no heating process in the household systems that are generally installed in developing countries; therefore, for each substrate, the optimum HRT should be found for the best biogas yield because the retention time affects the digestion process. The potential of cow dung, sheep and pig manures in the plastic reactor was studied in Ethiopia, showing how at 25- 28°C, a burnable gas with more than 60% methane was obtained from cow dung and sheep manure after 20 days of retention, while the substrate of the pig needed more time (Gemechu, 2020). In northern Brazil, the biogas production per kilogram of goat manure was approximately.54 L/kg in a modified floating model with a volume of 11.3m^3 (Borges Neto et al., 2010).

However, animal manure can slow digestion due to its low carbohydrate content (Surendra *et al.,*2014), and can generate a high concentration of ammonia, which is unfavorable for methanogens(Fujino *et al.,* 2005). Mixing manure with other organic waste can create the optimal waste combination for the co-digestion process to improve biomethane yield in terms of quality and quantity. In general, the interaction within different waste streams directly determines the biogas yield (Bharathiraja *et al.,* 2018). In co-digestion, the mixture of animal manure with an organic fraction rich in carbohydrates and low in ammonia has the remarkable ability to enhance biogas production. And vice versa, agricultural residues with high VS, high fermentable constituents, and low moisture benefit from co-digestion with animal manure or sludge because of their high ammonia content. Compared to reactors supplied with manure alone, volumetric methane production can increase to 65% in reactors fed with waste and 30% VS of crop residues such as straw, sugar beet tops, and grass (Lehtomäki *et al.*, 2007). Co-digestion showed promising results using several mixtures of food waste and dairy manure at 35°C; a manure/food waste ratio of 52/48% produced methane yields 311 L/kg VS after 30 days of co-digestion. Compared to raw manure, food waste contained higher VS (ca. 241 g/kg) it means higher energy content, which is desirable with regards to biogas energy production (El-Mashad and Zhang, 2010).

Depending on the different growth temperatures of the methanogenic microorganisms, the working temperature ranges can be defined as psychrophilic (under 25°C), mesophilic (30-40 ° C) and thermophilic (50-60°C). Anaerobic digestion is a process that is sensitive to temperature (Alvarez and Lidén, 2008). Because simple systems such as those used in rural areas in developing countries work at ambient temperature, HRT should be selected considering local temperature conditions to give bacteria adequate time to transform feedstock into biogas. Depending on the climatic conditions, the HRT varies from 10 to over 100 days (Gunnerson and Stuckey, 1986). At high altitudes such as the Peruvian Andes (psychrophilic conditions), HRT is needed between 60 and 90 days (Ferrer *et al.*, 2011). In such high-altitude and cold climates, fluctuation in temperature also represents a problem for biogas production. In Andean villages, low-cost tubular digesters were adapted by replacing the roof with a greenhouse. However, itwas not always successful in maintaining a digester slurry temperature higher than the ambient temperature (Alvarez and Lidén, 2008).

On the other hand, positive results were obtained from the modification of a floating drum modelin Indian villages located at an altitude of 1600 to 2200 m, where the diurnal temperature fluctuates from 8 to 35 ° C during the year. This fluctuation results in a reduction in gas production during winter by 23–37%. Improvement in insulation kept the operating temperature in good order. That was achieved by enfolding the system inside a greenhouse or using hollow bricks for the construction, placing straw insulation around the digester, or adding hot water in the input feedstock material. These modifications allowed for continuous biogas production of around 1.6 to 2.6 m3 / day throughout the year (Lohan *et al.*, 2015). Solar-biogas hybrid systems have been proposed in which heating provided by a solar collector has been provided to maintain the right temperature for anaerobic bacteria to produce biogas (Wang *et al.*, 2017).

In tropical regions with mesophilic conditions, HRT can range from 20 to 60 days (Ferrer-Martí *et al.*, 2018). In Bangladesh, rural dome-type digesters showed a retention time of approximately 40-50 days from a single feedstock such as cow manure (Khan and Martin, 2016). In Nigeria, thetotal biogas produced from poultry and cassava waste was 1.5 m^3 after 42 days in a prototype polyethylene system of 1 m^3 at an ambient temperature of 33.6 ° C (Ezekoye *et al.*, 2011). It is important to keep in mind that while temperature will affect biogas, feedstock security (or availability) influences the operation of the system (Naik *et al.*, 2014). For fueling a household stove twice per day in a family of five people, manure from one pig, five cows, or 130 chickensis required to have approximately 1.5 m^3 of biogas (Bond and Templeton, 2011). The collection of sufficient water and manure is among the limiting factors; In many parts of sub-Saharan Africa, although households possess adequate livestock, the nature of the grazing (nomadic, semi-nomadic, or free) may hinder the collection of manure to feed the biogas digesters (Mwirigi*et al.*, 2014). A digester volume of 1.3 m^3/capita requires approximately 0.05 m3/day of water for each cow and 0.01 m^3/day for each pig that supplies manure to the digester. Such a large amount of water can hardly be provided in areas of low water availability. In sub-Saharan countries, the water needed for digestion can be provided using recycled water (gray water), suchas domestic water, rainwater harvesting and aquaculture (Bansal *et al.*, 2017).

All rural small-scale and household digester models require daily operation and maintenance. Everyday operations include feeding, digester handling, and control of biogas outflow. Both brick and plastic tubular digesters are supplied with organic waste diluted with water in different proportions. The most challenging maintenance for users involves removing sludge from the digester, blocking possible cracks in the fixed digesters, and repairing damages in plastic systems(Ferrer-Martí *et al.*, 2018). Because the functionality of the digesters installed depends on continuous management and supervision of operation and maintenance, specific programs are often implemented to develop ownership and participation in the use of biogas systems (Tigabu*et al.*, 2015). Sensitivity analyzes demonstrated that small digesters are more environmentally sustainable if biogas leakage and release are avoided (Ioannou-Ttofa *et al.*, 2021).

2.2 Pros and Cons of Biogas Production

Biogas generators extract by-products from organic waste (including human and animal excreta, food items, etc.) which can be used to replace traditional fuels and fertilisers. Biogas generators produce 2 useful products:

1. Biogas – biogas is a natural gas which can be used directly as a fuel for cooking and heating orused to run a converted generator for electricity production.
2. Fertiliser – digested sludge from the bottom of the biogas generator and over-flow effluent water can be used as a fertilizer for crops

The benefits of biogas generators are explicitly listed below and should be made clear when users suggest the construction of the biogas generator to improve speed and likelihood ofacceptance.

1. Biogas generators provide a safe and cleaner way of storing excreta and subsequently bringabout related advantages linked to safe sanitation
2. Biogas generators provide free fuel for cooking, heating and lighting
3. Biogas generators provide fertilizer for crops
4. Biogas requires far less time and effort to collect than other fuels (e.g. wood)
5. Biogas reduces the need for wood and therefore reduces deforestation and the burden onwomen of collecting wood
6. Biogas does not create smoke and, therefore, reduces health problems caused by burning otherfuels indoors.
7. Biogas is environmentally friendly and does not release as many greenhouse gases whenburned compared to other fuels
8. Dangerous bacteria in the faeces are killed during digestion in the biogas generator

Biogas has an energy density of 6kWh/m3. 1m3 of biogas has the approximate equivalent energyof some common fuels.

2.2.1 Biogas serves to reduce energy poverty in developing countries.

In some countries, rural people do not even have access to fossil oil and kerosene because oftheir price or shortage; these people are forced to meet their energy needs using traditional and inefficient resources. As described, such practices represent significant health, environmental, economic and social issues for these communities. Today, in the context of sustainable development, it is imperative to provide these regions with access to clean, affordable, and renewable energy. Help people transform animal manure, crop residues, and domestic waste into a more efficient energy carrier, such as biogas, provide clean and reliable energy and conserve the local and global environment (Surendra *et al.*, 2014). It is evident how decentralized biogas production offers several opportunities to accelerate the transition to sustainable developmentand circular economy with positive economic effects on local livelihood (Lyytimäki, 2018). Biogas is an energy source that is useful for people to meet their energy needs without using fossil fuel (Amini *et al.*, 2013).

In Northern Brazil, a biogas volume of 1 m3 from manure was equal to 0.75 L of gasoline (Borges Neto et al., 2010). Small-scale biodigesters produce about 2 to 4 m3 / day biogas, sufficient to meet the cooking lighting needs of a family (Bharathiraja *et al.*, 2018). The biogas potential in Colombia showed that 80% of propane, which is traditionally used fuel, could be replaced by biogas; results showed that a low cost tubular digester in polyethylene with a total volume of 9.5 m3 and cattle feed produces enough biogas to supply cooking of five hours/dayfor five people (Castro *et al.*, 2017). In India, positive achievements were obtained using different design models simultaneously; It was possible to produce approximately 40.5 m3 biogas/day and supply the community of 48 households that had cooking needs of 0.85 m3/day each (Singh and Kaushal, 2016). In Bangladesh, approximately eight heads of cattle per household were needed to cover the need for cooking gas, electricity, and drinking water (Khan*et al.*, 2014). In Nepal, 0.33 m^3 of biogas fulfills the energy needs per capita per day (Centre for Energy Studies Institute of Engineering, 2001). In Israel, post-nomadic Bedouins families adopted a system of 7.5 m^3 fueled with goat manure and straw that provided biogas for cooking and for powering a little refrigerator (Pilloni *et al.*, 2020). In Bali, approximately 30 m3 of biogas / month using cow manure can supply the energy need for a family size of 5 to 6 people (IRENA, 2016).

Small-scale biogas technology embodies the opportunity to address the energy access issue for low-income developing countries (Somanathan and Bluffstone, 2015). Biogas digesters canreduce energy poverty (Amigun and Blottnitz, 2007, Antoine *et al.*, 2014), and provide clean energy for cooking and lighting in rural areas where energy infrastructure is lacking (Rajendran*et al.*, 2012).

2.2.2 The relevance of small-scale biogas systems to the regional development of rural areas in developing countries

The literature study discloses how small-scale biogas systems benefit the local family, village and surrounding communities in rural areas of developing countries. Anaerobic digestion, even on a small scale, represents an efficient waste treatment, and offers a source of clean energy (biogas) suitable for cooking, heating, electricity generation, and a digestate with a high fertilizervalue. It is a widespread opinion that anaerobic digestion implemented in poor rural areas can help achieve several Sustainable Development Goals (SDGs), positive health impacts and sanitization, preservation of soil and water (Breitenmoser *et al.*, 2019), reduction of greenhouse gas (GHG) emissions, gender empowerment and education (Yasar *et al.*, 2017), and an accessible and affordable source of clean energy (SDG7 Progress – 2020).

The use of bio-digesters to treat human sludge and animal manure significantly improves the hygiene situation of rural areas that lack adequate infrastructure to collect and treat wastewater, unmanaged human and animal waste. The use of bio-digesters can reduce infectious diseases such as diarrhea, cholera, and tuberculosis. Biodigesters also reduce the environmental impact (ecological, health, esthetic) of the spreading of waste in rural areas and reduce the danger of sewage percolating into the groundwater sources pumped for drinking water. In addition, it contributes to the reduction of GHG emissions. It was calculated that processing liquid and solid manure through anaerobic digestion reduces the potential impact from 4.4 kg equivalents of carbondioxide (CO_2) equivalents to 3.2 kg equivalents of CO_2 compared to traditional manuremanagement (Vu *et al.*, 2015).

Bio-digesters represent a great alternative to the inefficient use of traditional biomass such as fuel-wood, agricultural residues, and dried dung. Rural areas around the world suffer from the loss of forest land due to the illegal collection of firewood. The installation of bio-digesters and the use of biogas can provide a substitute for firewood and save forests. Also, fuel oil and kerosene are widely used in rural areas for cooking and lighting purposes, especially in developing countries. Biogas is an excellent replacement for these fossil fuels and can save people hundreds of dollars every year. In addition to that, countries with large amounts of rural areas are usually poor and oil-importing countries. The use of biogas can save those countries millions of dollars every year.

The use of biogas as a clean source of energy for cooking also includes important health benefits.Reduce exposure to indoor smoke and soot, reduce respiratory and eye diseases, reduce fatalities caused by carbon monoxide poisoning, and offer a significant reduction in RSPM in indoor environments.

Biogas use has many positive social outcomes in education and gender equality and generates employment opportunities for rural communities. The lack of enough light in rural areas in developing countries prevents students of all ages from having enough light to study or even participate in educational activities in the evenings. Biogas in gas lamps provides enough fuel for lighting and provides more study hours in the dark (Gautam *et al.,* 2009). Furthermore, in such poor areas, women are responsible for securing water and energy (Lohan *et al.,* 2015; Yasar *et al.,* 2017, Katuwal and Bohara, 2009). Having a bio-digester at home will save women tens of hours of collecting firewood. This time can be used by women for other activities such as educationand socializing. In addition, burning biogas does not generate particulate matter or soot that pollutes the homes, saving women cleaning time (Surendra *et al.,* 2014, Gautam *et al.,* 2009). Moreover, an increase in employment in rural areas was recognized as the positive impact of small-scale biogas installations. These news opportunities mainly involved women and professionals in education, environment, agriculture, and technical professions related to the construction and maintenance of systems.

The use of biodigesters reduces the use of chemical fertilizers. In addition to biogas, the biodigesterproduces organic fertilizer rich in nutrients, such as nitrogen, potassium, and phosphorus. This organic fertilizer can replace commercial fertilizers and save farmers in rural areas thousands of dollars every year. Additionally, this liquid fertilizer can maintain the use of water for irrigation. Therefore, biodigesters maximize the valuable fertilization properties of recycled waste for agriculture; This benefit will lead and promote the economic development of the local family.

2.2.3. Challenges of biogas systems in rural areas for communities in developing countries

Despite all of the benefits biodigesters have for rural communities, some biogas systems in rural areas do not meet the expectations due to technology, maintenance, and technical support. All those aspects induce a discontinuity of digester operation as documented for China, in the Guizhou Province, 62.03% of household biogas were continuously operating while 36.72% werediscontinued (Wang *et al.*, 2016). In some other cases, the challenges represent the reasons for technology's abandonment (Lwiza *et al.*, 2017). This section summarizes the challenges biogas systems are facing in rural areas.

In cold rural areas, owners of biogas system lack the right technology to maintain thermal conditions for a high rate of biogas production (Sommer, 2007). The people of these areas face this challenge, especially in winters when the energy need is greater than in other seasons. As described above, the household biogas digesters are made of bricks or concrete and built just below the ground surface where the digesters temperature is very close to the ambient temperatures. Thus, without the appropriate heating or hybrid technologies, the efficiency of the household biodigesters remains low and unstable under these conditions. Design solutions have been developed to maintain the right temperature for biogas production, such as insulating digesters or combining them with other heating technology (i.e., solar water heaters). However, these solutions can be difficult to implement for people in rural areas.

The lack of technical knowledge and building capacity in rural areas is another critical factor leading to low biogas production rates. People in rural areas lack access to formal education, awareness of environmental issues, agricultural techniques, and adequate knowledge on how to operate biodigesters. In some countries, farmers receive government financial support to construct biogas systems. In many cases, this governmental support is not accompanied by technical support and safety measures to adequately manage the biodigesters (Surendra *et al.*, 2014; Mittal *et al.*, 2018; Gautam *et al.*, 2009; Jiang *et al.*, 2011). Furthermore, lack of knowledge of the ratio between biodigester size and organic waste volume can lead to low biogas production rates and digestate pollution near the biodigester. That may cause odour emissions, eutrophication of surface water, and contamination of groundwater. As described below, only a rational design of the small-scale system, along with proper construction, continuous cleaning, and maintenance, affects the productivity and environmental footprint of the system (Ioannou-Ttofa *et al.*, 2021).

In general, rural areas are located in remote areas where it is difficult to reach and run educational programs and maintenance. In addition, the lack of governmental follow-up and capacity building programs leads to poor maintenance and operation of biogas plants. Inappropriate use of liquid fertilizer may attract flies and mosquitoes to the biodigester and pose challenges to biodigester users. Additionally, this may create negative publicity for biogas plants among people.

Low or discontinuous biogas production due to improper operation of the biodigester, technical barriers, lack of feedstock (animal manure or food waste), and low level of awareness can lead to inadequate biogas supply. Thus, people in rural areas are discouraged from using biodigesters on a daily or seasonal basis. It may lead to low adoption rates in rural areas and force people to switch to more reliable fuel sources.

2.3 Small- Scale Biogas Production in Developing Countries

Rural areas in developing countries: defining the context

The world's rural population has been growing slowly since 1950. There are 3.4 billion people living in rural areas around the world, 90% of them live in Africa and Asia. India (893 million) and China (578 million) represent 43% of the world's rural population. As the rural population worldwide became more sedentary and grew in population and density, the related environmental and public health problems increased. The population growth determined anincrease of consumption needs, and several effects are due to such increased demands. The most prevalent demand is the need for food that can be met through intensification and expansion of agricultural land use. These two responses to the increase in food demand are often led by a lack of technological innovation and efficient practices. In fact, if land is available, land extensification is more likely to happen; depending on the geographical area, communities may cut trees in lowland forests, use highland slopes in high mountainous regions, or remove brush in semi-arid zones. Therefore, in the absence of adequate environmental controls and rural policies, as has generally occurred in the past, the consequences have been deforestation, soil degradation, and desertification in areas already marked by poverty. The population growth determines an increase in energy demand for cooking and heating. In developing countries fuelwood is the cheapest and primary source of energy for cooking and heating. If fuel wood is available in the vicinity, local deforestation results; otherwise deforestation occurs elsewhere also at a long distance from the community (Bilsborrow, 1992). In addition to deforestation, which represents an urgent issue in the current era of climate change (Laramee and Davis, 2013), the use of fuel wood creates other concerns that need attention. In terms of environmental concerns, diffuse utilization of an inefficient biomass source contributes to greenhouse gas emissions (Mulinda *et al.*, 2013). In fact, biomass such as wood and charcoal, both used in poor rural areas, is not sustainable, and when partially burnt, it causes emissions that contribute to global warming (Bruun *et al.*, 2014). As a health concern, due to the use of wood stoves by rural households, a high level of exposure to Respirable Suspended Particulate Matter (RSPM) from the smoke fromwood stove fuels generates health hazards mainly for women and children (Kanagawa and Nakata, 2007). From the perspective of social-economic aspects, women and children are the main fuel wood gatherers (even from long distance), and the fuel wood is collected at the expense of their labour, time, and drudgery (Reddy, 2004), and it withdraws them from opportunities of education and income.

In developing countries, the rural areas suffer more than urban clusters from lack of basic infrastructure with low access rates to clean water, household sanitation (Kamp and Bermúdez, 2016), and waste management (Tock and Schummer, 2017), which determine high public health risk, which is exacerbated by the continuous growth of population and density. The absence of such infrastructures drives rural communities toward practices that negatively affect their surroundings with contamination and pollution of land, water, and air due to unmanaged organic waste from the household and livestock (Mshandete and Parawira, 2009; Cho *et al.*, 2000). The practices of burning organic waste such as animal dung and crop residues represent how rural communities meet their cooking and heating needs, although it is inefficient and detrimental to health (Ferrer-Martí *et al.*, 2018). Rural areas also suffer from the limited or absent electricity supply and distribution infrastructures, so rural populations have low access to electricity. It was estimated that 770 million people in 2019 were without electricity access; in Africa in the year 2020 there were 592 million people without electricity access, and the Sub-Saharan represents the region where the access deficit is higher (World Energy Outlook, 2020). Such a struggle in energy access drives rural populations to rely on traditional biomass resources or to become dependent on imported fossil fuel derivatives. However, as already described, these resources have negative impacts on health and the environment and weaken those economies which are already fragile (Surendra *et al.*, 2014).

2.3.1 Developing countries: small-scale biogas programs for rural areas

Attention to small-scale biogas technologies has increased in recent decades worldwide, with rapid development and diffusion in rural areas in Asia, Africa and Latin America (Bond and Templeton, 2011). The mass dissemination was dependent on central government programs and long-term political support (Ortiz *et al.*, 2017). Between 1970 and 1985, China established program to promote and facilitate the installation of biogas in all rural household; the program brought the installation of 4.7 million household digesters by the end of 1988 (He, 2010). A further increase was observed starting from the end of the 20th century, China registered more than 26 million biogas household installations in 2007 (Teodorita *et al.*, 2008), and 43 million biogas users were counted in 2013 (Giwa *et al.*, 2020). Since 1981, India had the National Project on Biogas Development (NPBD) with various training and development programs and financial support (Lichtman, 1987). As a result of government subsidies, more than five million household biodigesters were installed in 2014 (26 Mittal *et al.*, 2018). In Latin America, the introduction of biogas technologies for households was driven by the energy crisis in the 1970s when the Latin American Energy Commission (OLADE) prompted installations in several counties.

Furthermore, the Biodigesters in Latin America and the Caribbean network (RedBioLAC) was created in 2009 to promote household, community, and farm-scale digesters in Latin America (Martí-Herrero, *et al.*, 2014). Bolivia is one of the countries involved in the network, with more than 1000 domestic biogas digesters installed in 2014 (Scarlat *et al.*, 2018). Many other small-scale biogas programs have been implemented to develop rural areas (Ferrer-Martí *et al.*, 2018, Khan and Martin, 2016). In Africa, there was an increase of more than 44% in domestic digesters installed between 2011 and 2012, and approximately 60,000 digesters were installed in Burkina Faso, Ethiopia, Kenya, Tanzania, and Uganda in 2015 (Vasco-Correa *et al.*, 2018).

China has the highest number of biogas plants among the IEA Bioenergy Task 37 member countries, with more than 100,000 biogas plants, in addition to the 100,000 biogas plants. China also has many household biogas units.

In countries like Australia and the UK, landfills are the largest source for production of biogas, while the contribute very little in countries like Germany and Switzerland, showing the low level of landfilling of organic waste material.

In most of the Task 37 member countries, biogas is mainly used to generate heat and electricity. Sweden is different because more than half of their biogas produced is being used as fuel for vehicle. Germany is second in absolute members in terms of biogas as a transport fuel.

Germany and Sweden have had the largest markets for biomethane in recent years, but a growing interest is seen in other countries as well. UK has now taken over the second position from Sweden, using more biomethane for heat and electricity generation and also as vehicle fuel.

Financial support systems are very difficult from country to country. Various systems with feed- in tariffs, investment grants and tax exemptions exist. A clear correlation between the financial support system and the way biogas is utilized is evident in the Task 37 member countries. In countries like the UK, Germany and Austria, feed-in tariffs for electricity have led to most of the biogas being used to produce electricity, while the system with tax exemption in Sweden favours utilization of the biogas (biomethane) as a vehicle fuel. In several countries, financial support systems have led to an increased share of biogas in the gas grids.

Lastly, there are many exciting innovative biogas projects going on, including dry digestion, CO_2 utilization and cross-sectoral synergies.

In many other cases, the success of biogas implementation was due to the combination of governmental support and non-profit organizations. The Netherlands Development Organization (SNV), based in The Netherlands, had supported national biogas programs that affected more than 2.9 million people on different continents (Ghimire, 2013)

Biogas is a methane-rich gas that is produced from the anaerobic digestion of cellulosic matter. The composition and properties of biogas are provided in Table 2. The main interest in biogas comes from Asia and the Pacific region. Biogas has had very little impact in Latin America. (Itodo *et al.*, 2007). The West sees biogas technology as appropriate, while the Developing Countries think that it is a second-class technology. Biogas is used in Tanzania, Burundi, Cameroon, Benin Republic and Nigeria. About 150 mt of biogas will be produced globally by 2040, over 40% of which is in China and India (Itodo *et al.*, 2019).

Table 2. Summary of other Countries' capacities and support systems (Arelli *et al.*, 2018)

Country	Installed Biogas Power Capacity in 2016 (MW)	Support for Biogas Projects
Austria	194	Feed-in-tariff, which varies based on the capacity, the technology of the plant and origin of the biogas
Brazil	451	Incentives for energy from waste resources
Bulgaria	30	Projects receive up to 20% grant
Czech Republic	369	Subsidy to support construction
Denmark	110	Uses "Green Pricing" to provide incentives for manufacturers that use biogas to generate electricity.
Italy	1387	Fee-in-tariff, which favours smaller plants with less than 500kW capacity
South Africa	22	Investment incentives
Sweden	2	Vehicle fleet to be independent of fossil fuels by 2030. Methane will be one of the principal fuels
Thailand	435	Increase biogas capacity to 600 MW by 2030
United Kingdom	1667	Feed-in-tariff
United States	2438	The federal government provides tax incentives, grants, performance-based incentives, soft loans. Various state governments provide tax credits and grants.

* Capacity shown is for installed power only. Some of the countries also use a large portion of biogas as a transportation fuel.

Table 3. Example of commercial Biogas Digesters in Some African Countries (Bansal *et al.*, 2017)

Area	Developer or Biomasss Source	Capacity (MW)	Country
Alice	University of Port Hare	0.2	South Africa
Athlone	Clean Energy Africa and Wastemart	4.0	South Africa
Bredasdorp	iBert	0.10	South Africa
Cavalter	IBert	0.50	South Africa
Cavalter	EnviroServ/Chloorkop LFG Cullinan	0.19	South Africa
Darling Uilenkraal	Uilenkraal dairy farm	0.60	South Africa
Durban	Bisasar road LFG	6.00	South Africa
Durban	Marrianhill LFG	1.50	South Africa
Grabouw	Elgin Fruit and Juices	0.50	South Africa
Jan Kempdorp	iBert	0.135	South Africa
Jan Kempdorp	Jacobsdale	0.15	South Africa
Johannesburg	WEC Projects/NorthernWasteWater Treatment Works	1.20	South Africa
Johannesburg	Robinson Deep	19.00	South Africa
Klipheuwel	Farmsecure	0.60–0.70	South Africa
Mossel Bay	Biotherm Energy	4.20	South Africa
Paarl	Drakenstein municipality	14.00	South Africa
Pretoria	Bio2watt/Bronkhorst-Spruit	4.60	South Africa
Riverdale	iBert	0.10	South Africa
Riverdale	Robertson	0.15	South Africa
Springs	BiogasSA/Morgan Springs Abattoir	0.40	South Africa

Springs	Selectra	0.50	South Africa
Springs	Selectra	1.00	South Africa
Springs	Selectra	1.00	South Africa
Chaka	Afrisol	0.060	Kenya
Dagoretti	Slaughterhouse waste	0.030	Kenya
Isinya	P. J. Dave Flower Farms Ltd (PPP)	0.10	Kenya
Keekonyoike	Slaughterhouse waste	0.020	Kenya
Kericho	James Finlay Ltd	0.160	Kenya
Kilifi	Pine Power Ltd	0.150	Kenya
Naivasha	Bio-joule Kenya	2.20	Kenya
Sagana	Oilvado Company Ltd	0.340	Kenya
Simbi Roses	Ereka Holdings Ltd (PPP)	0.055	Kenya
Adeiso	Assorted fruit waste and poultry manure	0.90	Ghana
Ashaiman	Market and faecal waste	0.10	Ghana
Kwae	Oil palm waste	2.00	Ghana

PPP—Public-Private Partnership collaboration with the Ministry of Energy; LFG—Landfill gas.

Table 4: Composition of biogas (Itodo *et al.*, 2019).

CONSTITUENT	*COMPOSITION (%)*
Methane	55–65
Carbon dioxide	25–45
Oxygen	0.1
Carbon monoxide	0.1
Hydrogen	10-Jan

Nitrogen	3-Jan
Hydrogen sulphide	Trace

2.3.2 Biogas production and potential in developing countries

The biogas energy supply is a valuable sector for the bioenergy industry. In 2017, 1.33 EJ of biogas was produced globally; representing 2% of the total biomass produced for energy purposes, but it has the potential to develop much more. Europe leads in biogas supply for more than 50% of the global supply, Asia follows it with 31%, and America with 14% (Association, 2019).

Although developing countries showed more barriers to biogas application, some countries such as China (Wang *et al.*, 2020), South Africa (Mutungwazi *et al.*, 2018), Ghana, Rwanda, and Tanzania (Amigun and Blottnitz, 2007) produce biogas from large scale institutional plants using similar technology implemented in developed countries.

However, in developing countries, biogas is predominantly produced on a small and domestic scale. In China, the 43 million small-scale biogas installations contributed to generating, togetherwith the large-scale plants, about 15 billion m3 of biogas in 2014. It corresponds to 9 billion m3 bio-methane; moreover, the annual potential was calculated around 200–250 billion m3 (Scarlat *et al.*, 2018). In Bangladesh, 100,000 small biogas systems were planned to be built by 2020, with an average c.a. 50 kW (Bertsch and Marro, 2015).

Currently, Bangladesh has nearly 100,000 biogas plants and more than 58,000 plants are financed and monitored by Infrastructure Development Company Limited (IDCOL, 2021).

It is difficult for developing countries to find in the literature an exact number on the real contribution of small-scale biogas systems to the overall production of national renewable energy. However, it should be noted that for regions where the energy access deficit is greater, domestic livestock biogas generation represents an enormous energy gain to move a step fromabsolute energy poverty. For example, domestic biogas generation potential assessed in Nigeria showed an annual biogas projection of 138.7 X 106 m^3 from livestock, equivalent to 0.48million barrels of crude oil (Adeoti *et al.*, 2001).

2.4 Biogas Production

Anaerobic digestion is a technology that converts waste into energy. The produced biogas is considered as the primary energy output. The percentage of methane in the biogas is responsible for its calorific value, which is generally considered high (Salunkhe, *et al.*, 2012). Biogas can substitute oil, coal, and natural gas. Biogas can also be upgraded and directly used in natural gas pipelines and vehicles. The exploitation of fossil fuels and natural resources has increased greenhouse gas (GHG) emissions, deforestation, infertility of land, consumption, and waterpollution. Biogas as a source of energy can help mitigate these problems and reduce global warming. In addition, using anaerobic fermentation to convert organic waste into fuel has many advantages over the use of crops to generate biofuels: it limits land use, food scarcity, and biodiversity damage. Thus, biogas represents an ethical choice for energy production (Nevzorova and Kutcherov, 2019). In terms of net energy generation, methane from anaerobic digestion is considered competitive in terms of efficiency and costs compared to other biomass energies (Chynoweth *et al.*, 2001), and it is better from an ecological point of view (Edelmann *et al.*, 2000).

Those benefits are already attributed to anaerobic digestion and biogas technology worldwide; however, the contribution of small-scale biogas installations to rural areas in developing countries has a wealthier meaning, and this chapter is aimed to disclose and discuss such value.

The design of biogas technology varies depending on the country, climatic conditions, and the feedstock availability; moreover, it depends on the policy regulations such as waste and energy programs and energy accessibility and affordability. Thus, biogas production may vary from different ranging set-ups, from backyard systems to large industrial plants. In developing countries, the domestic small-scale biogas installations, also called household anaerobic digesters, are the most diffused systems in the rural areas (Teodorita *et al.*, 2008). Those systems volume generally ranges up to 10 m^3 (Bond and Templeton, 2011). The size of the digester is limitedby the volume of feed that is available from the household and is easily accessible; the most common feedstocks are animal manure, food waste, small agriculture waste, and sewage sludge. Household systems represent an effective strategy to improve the quality of rural household life because they simultaneously advance sanitation and rural ecology and increase energy availability and income from small agricultural activities (Laramee and Davis, 2013).

The most common energy use of household biogas is for cooking and lighting (Amini *et al.*, 2013). Those systems have been successfully used worldwide with the participation of governments and institutions supporting the diffusion of household biogas through subsidies and programs of planning, design, construction, and maintenance (Cheng *et al.*, 2014).

2.4.1 Phases of Anaerobic Digestion

The process of anaerobic digestion takes place through four successive stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis; the anaerobic digestion process is dependenton the interactions between the diverse microorganisms that can carry out the fouraforementioned stages (Verma, 2002). In single-stage batch reactors, all wastes are loadedsimultaneously, and all four processes are allowed to occur in the same reactor sequentially; the compost is then emptied after at the conclusion of a given retention period or the cessation of biogas production (Verma, 2002). Figure 5 depicts a simplified flow of the four digestion stages described below.

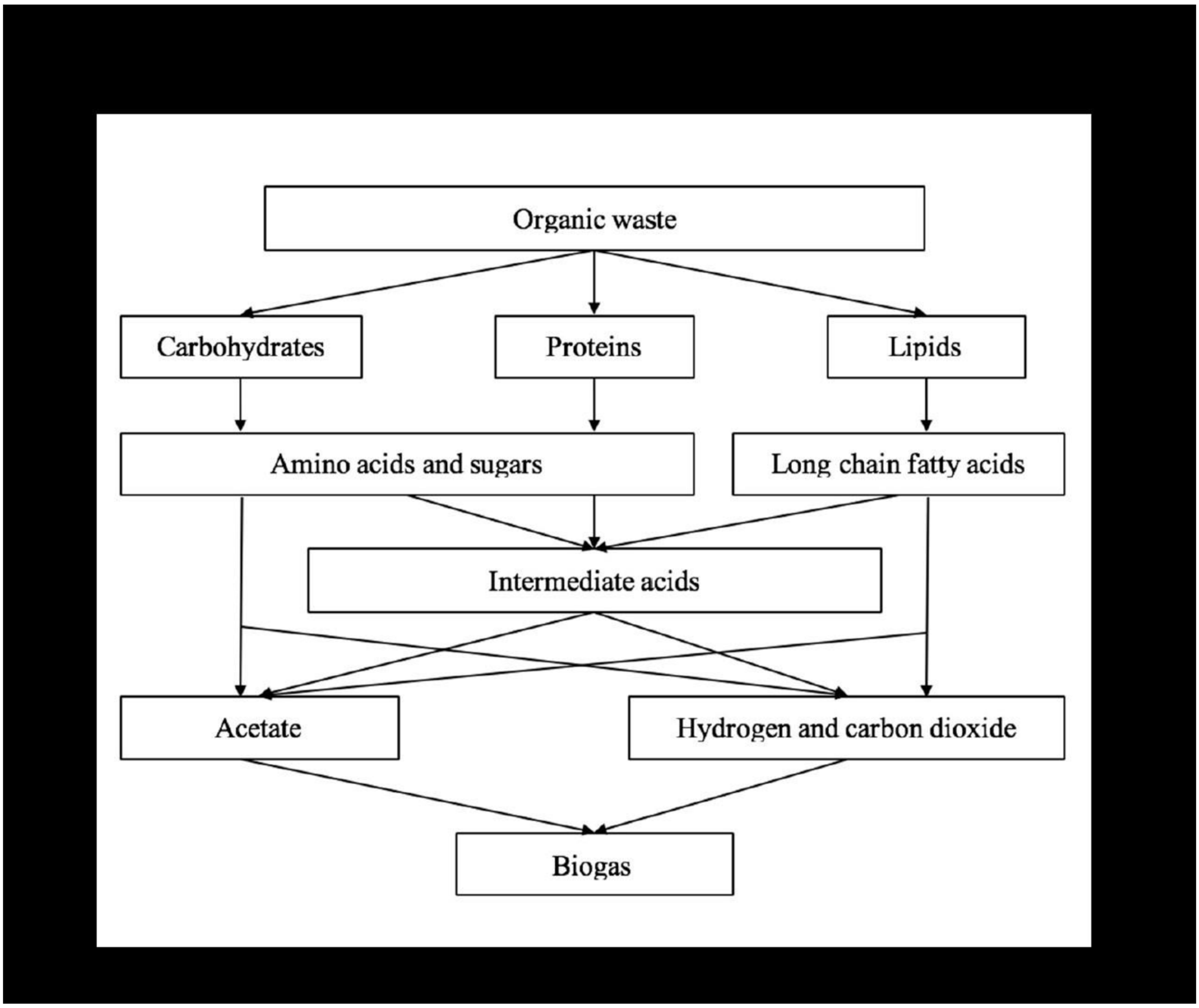

Figure 5. The simplified scheme of pathways in anaerobic digestion (Lohri et al., 2013).

2.4.2 Hydrolysis

Anaerobic digesters typically encounter organic biomass that contains complex polymers that are inaccessible to microorganisms are not broken down further by hydrolysis or pre-treatments (Gujer et al, 1983). As a result, the process of hydrolysis serves the purpose of organic macromolecules into its smaller components, which in turn can be utilized by acidogenic bacteria. While hydrolysis can exist as an electrochemical process, in anaerobic digestion, it mostly exists as a biological one. In the process of hydrolysis, hydrolytic bacteria are able to secrete extracellular enzymes that can convert carbohydrates, lipids, and proteins into sugars, long chain fatty acids (LCFAs), and amino acids, respectively (Li et al., 2011). After enzymatic cleavage, the products of hydrolysis are able to diffuse through the cell membranes of acidogenic microorganisms (Van Lier *et al.*, 2008). However, it is important to note that certain substrates, such as lignin, cellulose, and hemicellulose, may find it difficult to degrade, and can be inaccessible to microbes due to their complex structures; enzymes are often added to enhance the hydrolysis of these carbohydrates (Lin *et al.,* 2010). Hydrolysis can be a rate-determining step, although previous research has also demonstrated that methanogenesis could exist as a rate-determining step depending on the ratio of hydrolytic to methanogenic microorganisms (Luo *et al.,* 2012, Ma *et al.,* 2013). Due to the importance of hydrolysis in the kinetics of anaerobic digestion, a great deal of attention has been turned towards methods for expediting hydrolysis in anaerobic digesters. Various waste pre-treatment options are being researched and utilized to optimize hydrolysis, especially digesters that digest heavily lignocellulosic waste (Kumar and Sharma, 2017). Generally speaking, hydrolysis has, on its own, an optimum temperature between 30–50 _C and with an optimum pH of 5–7, althoughthere is no evidence of improved hydrolytic activity below a P^H of 7 (Azman, 2016).

2.4.3 Acidogenesis

By absorbing the products of hydrolysis through their cell membranes, acidogenic microorganisms are able to produce intermediate volatile fatty acids (VFAs) and other products. VFAs constitute a class of organic acids such as acetates, and larger organic acids such as propionate and butyrate, typically in a ratio varying from 75:15:10 to 40:40:20 (Bergman, 1990). Even then, smaller amounts of ethanol and lactate may be present (Van Lier *et al.,* 2008). The specific concentrations of intermediates produced in the acidogenesis stage may depend on the conditions of the digester; it has been reported that VFA concentrations can fluctuate significantly for digesters operating at different pH, with different studies presenting seemingly contradictory results (Huang *et al.,* 2015, Wu *et al.,* 2010).

Unlike other stages, acidogenesis is generally believed to proceed at a faster rate than all other stages of anaerobic digestion, with acidogenic bacteria having a regeneration time of fewer than 36 h (Deublein and Steinhauser, 2008). With the rapidity of this stage in mind, it isimportant to note that while VFA production creates direct precursors for the final stage of methanogenesis, acidification of VFA is widely reported to be a cause of digester failure(Akuzawa *et al.,* 2011). A somewhat similar anaerobic process is present in bokashi composting, a composting practice in which food wastes and a microbial inoculant are left to degrade anaerobically, creating a highly acidic final product that can be used as a liquid and dry fertilizer (Yamada and Xu, 2001).

Finally, in protein-rich wastes such as sewage wastewaters, it fits to examine the process of VFAproduction from amino acids. Amino acids generally degrade into VFAs in pairs via the Stickland reaction, with single amino acid degradation also possible when hydrogenotrophic bacteria are present, although this latter process is known to be slower than the Stickland reaction (Kovács *et al.*, 2013). One important product of the amino acid breakdown is the production of ammonia from deamination, which, at sufficiently high concentrations, is known to also be an inhibitor of anaerobic digestion (Kovács *et al.* 2013, Park *et al.*, 2014).

2.4.4 Acetogenesis

With the production of acetate through acidogenesis, a portion of the original substrate has already been rendered into a substrate suitable for acetolactic methanogenesis (Fournier and Gogarten, 2008). However, other produced higher VFAs have yet to be made accessible to methanogenic microorganisms. Acetogenesis is the process by which these higher VFAs and other intermediates are converted into acetate, with hydrogen also being produced (Hansen and Cheong, 2013).

The hydrogen produced during acetogenesis complicates the discussion of an interesting syntrophic relationship that is present in anaerobic digestion, the transfer of hydrogen between species. Although, acetogenesis is a producer of hydrogen, an excessive partial pressure is shown to be harmful to acetogenic microorganisms (Dinopoulou *et al.*, 1988). However, due to thepresence of hydrogenotrophic methanogens, hydrogen can be consumed rapidly whilemaintaining partial hydrogen pressures at a level favourable to acetogenesis by creating anexergonic reaction (Stams and Plugge, 2009).

At the same time, lipids undergo a separate pathway of acetogenesis via acidogenesis and _- oxidation, where acidogenesis produces acetate from glycerol and _-oxidation produces acetate from LCFAs (Cirne *et al.*, 2007). With this in mind, it would be useful to be mindful that only LCFAs with an even amount of carbons can degrade to acetate; LCFAs with an odd amount of carbons are first degraded to propionate (Cirne *et al.*, 2007).

2.4.5 Methanogenesis

Methanogenesis marks the final stage of anaerobic digestion, where accessible intermediates are consumed by methanogenic microorganisms to produce methane (Ferry, 2010). Methanogenic microorganisms represent a group of obligate anaerobic archaea; as a testament to the acute sensitivity of methanogenic microorganisms to oxygen, it was found that 99% of Methanococcusvoltae and Methanococcus vannielli cells had been killed within ten hours upon exposure to oxygen (Kiener and Leisinger, 1983).

In addition to a sensitivity to oxygen, methanogenic microorganisms are confined to a small selection of substrates. Typically, acetolactic methanogenesis from acetate accounts for approximately 2/3 of methane production and hydrogenotrophic methanogenesis account for approximately the remaining 1/3 of methane production; however, methanogenesis from methanol, methylamines, and formate has also been observed (Belay *et al.,* 1986, Lovley and Klug, 1983). With regards to the environmental needs of methanogenesis, methanogenic microorganisms tend to require a higher pH than previous stages of anaerobic digestion, in addition to a lower redox potential, the latter requisite having caused significant trouble for laboratory cultivation (Wolfe, 2011). At the same time, methanogens appear to have a significantly slower regeneration time than other microorganisms in anaerobic digestion, upwards of 5–16 days (Deublein and Steinhauser, 2008). However, some hydrogenotrophic species, such as Methanococcus maripaludis, have been reported to have a doubling time of only two hours (Richards *et al.,* 2016). Although methanogenic species likely constitute the most sensitive microbial group present in anaerobic digestion, recent research has suggested that Methanosarcina spp. tend to be relatively robust, capable of withstand concentrations of ammonia, sodium, and acetate in addition to pH shocks at levels that would otherwise be detrimental to other methanogenic microorganisms (De Vrieze *et al.*, 2012).

In batch reactors, the end of methanogenesis is determined when biogas production stops, which can take about 40 days (Verma, 2002). Evaluations of the extent of digestion of a sludge can be taken from its volatile solid content and its ability to dewater (Wisconsin Department of Natural Resources. 1992).

2.5 Quantitative Evaluations of the Anaerobic Digestion Process

The following subsections describe the commonly used metrics used in quantitative evaluations of the anaerobic digestion process.

2.5.1 Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) provides a measure of biodegradable organics present in a sludge, and, in turn, can be used as a metric for the overall effectiveness of an anaerobic digester (American Public Health Association, 1965). BOD reflects values from the microbial metabolism of dissolved oxygen in a given sample of sludge over the course of five days. Ultimately, BOD is a value that can be used to determine the amount of dissolved oxygen neededto sustain aerobic microorganisms to in a sludge sample over an experimental period of fivedays, which in turn can be used to quantify the concentration of biodegradable organics present in sludge (American Public Health Association, 1965).

BOD testing is conducted in sealed bottles at a prescribed temperature and in a dark room to prevent any dissolved oxygen production from photosynthesis (American Public Health Association, 1965). Thus, BOD can be obtained from the difference in dissolved oxygen and the start and end of incubation after the dilution is taken into account. Alternatively, a variation of BOD, carbonaceous BOD (cBOD), is determined from a similar protocol, except a nitrification inhibitor is added to prevent the oxidation of ammonia, nitrogen, and nitrite (Delzer and McKenzie, 1999). It could be assumed that for sludges with a high protein content, such as wastewater, cBOD would be able to provide a more accurate measurement of the organics present. A similar measure that is used for the aerobic digestion of sewage waste is the oxygen uptake rate, in which a measure of biological activity is obtained from the consumptionof oxygen in an aerobic sludge over a given experimental period (EPA, 2001).

2.5.2 Chemical Oxygen Demand

Like BOD, chemical oxygen demand (COD) provides a measure of the oxygen present in a sample of sludge that can be consumed in a reaction with oxidizing agents (American Public Health Association, 1965). In anaerobic digestion, COD typically reflects the number of organicspresent in a sludge. The efficiency of anaerobic digestion can also be evaluated using COD;COD reduction can reflect the amount of degradation that occurs within an anaerobic digester, asit reflects the consumption of organics (Van Lier *et al.*, 2008).

In COD tests, a sludge is refluxed in excess with a solution of potassium dichromate and sulfuric acid. The use of potassium dichromate eliminates the need for nitrification consideration, since itcannot oxidize ammonia to nitrate (Sum Parameters, 2018). Upon completion of a reflux, the quantity of excess potassium dichromate can be determined by a titration against ferrous ammonium sulphate; the final COD value can be determined from the amount of potassium dichromate consumed in the initial reflux (APHA, 1965).

2.5.3 Relating Measures of Biochemical and Chemical Oxygen Demand

As described above, COD is typically calculated from a dichromate reflux, a process which can be completed within a few hours. In contrast, testing for BOD, a related but separate measure, typically takes five days, as instead of using strong oxidizing agents to oxidize a sludge sample, BOD testing relies on the use of aerobic bacteria to oxidize the biodegradable organics in a sludge sample. Generally, BOD testing is avoided due to logistical difficulties, especially due to the time required to complete the test, because obtaining results after five days no longer provides accurate information on the present conditions of the digester and is therefore unreliable inmaking judgments with respect to operational adjustments (Sum Parameters, 2018).

As COD measures all organics in a sludge, its value is understandably higher than that of BOD. Thus, the ratio of BOD to COD can be used to represent the biodegradable fraction of a sludge(Jouanneau *et al.*, 2014).

2.5.4 Carbon/Nitrogen Ratio

The carbon/nitrogen ratio (C/N ratio) of a substrate is a commonly-used characterization of nutrients. Considering the composition of carbohydrates, lipids, and proteins, it stands to reason that the most abundant source of nitrogen in an anaerobic digester would be from the degradationof proteins. Just as carbon is necessary at a certain concentration to provide a suitable substrate for digestion, nitrogen at a certain concentration is also necessary lest the protein formation for microorganisms be compromised (Zupanˇciˇc and Grilc, 2012). In a study conducted on dairy manure, it was found that increasing C/N ratios led to decreasing methane concentrations in biogas, with an optimum at a C/N ratio of 25:1 (Hills, 1979).

The C/N ratio has also been a subject of attention as co-digestion of multiple substrates has become increasingly utilized. For example, poultry manure has been known to have a relatively low fertility

C/N ratio due to a high ammonia content, possibly due to urea; as such, carbon-rich substrates such as straw may be co-digested to obviate the possibility of ammonia inhibition (Callaghan *et al.*, 2002, Wang *et al.*, 2012). In a more recent study conducted with mesophilic and thermophilic digesters for the co-digestion of dairy manure, chicken manure, and rice straw, an optimal methane potential and reduced ammonia inhibition were observed at C/N ratios of 25:1 for mesophilic digesters and 35:1 for thermophilic digesters (Wang *et al.*, 2014).

2.5.5 Factors of Anaerobic Digestion and Their Impacts

. Temperature

One of the most critical parameters influencing the performance of any AD process is temperature (Nie *et al.*, 2021). Methanogenic bacteria and volatile acid-forming bacteria are affected by temperature, and the enzyme activity that is secreted by these bacteria changes according to the temperature (Czatzkowska *et al.*, 2020). Therefore, it influences the formation of methane (Pramanik *et al.*, 2019). There are three temperature operating conditions for the AD process: psychrophilic (∞20 °C), mesophilic (∞35 °C), and thermophilic (∞55 °C) (Li *et al.*, 2020**)**. Most of the 2022, 10, 81 5 of 22 digestion processes occur under mesophilic andthermophilic conditions, and many studies have occurred under mesophilic conditions (Ryue *et al.*, 2020) due to its process stability, low energy consumption, and high bacteria diversity(Moset *et al.*, 2015). Thermophilic processes can provide several benefits, such as enhanced methane production, low retention time, fast degradability, and a high rate of pathogen destruction (Buffière *et al.*, 2018). On the other hand, plenty of the consequences are negative for the thermophilic process, which is considered more energy intensive, with low- process stability, five-fold greater accumulation of VFAs compared to mesophilic carried out at alow pH value, and high free toxic ammonia concentration (Ryue *et al.*, 2020). Other research studies support two-stage anaerobic digestion systems; the concept is to isolate the hydrolytic- acidogenic phase from the methanogenic phase to alleviate the drawbacks of the single-stage process (Srisowmeya *et al.*, 2020**)**. Additionally, the digestion of FW in a two-stage psychrophilic reactor generated a higher amount of biogas (0.800 m^3Kg^{-1} VS) than the single- stage mesophilic digester (0.751 m3Kg^{-1} VS) (Rusín *et al.*, 2020). On the other hand, the temperature presents a heating technique for the fermentation reactors.

The use of electromagnetic microwave radiation can precisely control the temperature inside the reactors and permit energy to be directed at the feedstock (Cantero *et al.*, 2019; this also decreases the energy losses caused by absorption by the reactor components (guilar-Reynosa *et al.*, 2017). It gives a positive energy balance (9.2 Wh d^{-1}) compared to a convection heating method (-112 Wh d^{-1}) in a study of methane fermentation of expired food products (Kazimierowicz *et al.*, 2021).

2.5.6 pH

pH is an essential parameter that affects the efficiency of the process indicating and controlling its stability (Xu *et al.*,2021). Furthermore, microorganisms are extremely sensitive to pH because different communities of bacteria require various pH ranges (Pramanik *et al.*, 2019); for example, acidogenic bacteria performed well in the pH range between 4.0 and 6.0 helping acidification of AD and VFA production (Srisowmeya *et al.*, 2020). Methanogens are responsible for the production

of methane gas; their pH range is narrow, around neutral value which is the optimal range for an efficient AD process. Maximum methane production was achieved at pH 7, while an 88% reduction of methanogen production was observed at pH 5.5 in continuous anaerobic digestion ofwaste-activated sludge (Latif *et al.*, 2017). In a study of the pH effect in anaerobic digestion of citrus waste, Eryildiz confirmed high methane production with a pH value equal to 7 (Eryildiz and Taherzadeh, 2020). At a pH value exceeded, the activity of methanogens is inhibited(Eryildiz and Taherzadeh, 2020; Caruso *et al.*, 2019). Furthermore, this high value increases ammonia concentrations and is displaced by free toxic ammonia (Rocamora *et al.*, 2020). Pre-treatment methods and co-digestion have a positive effect in controlling the pH value within the optimal range. El Gnaoui found that in the application of thermal pre-treatment of FW, in a temperature value between 60–100 _C, the pH fluctuated in the range of 7.29–7.76 (El Gnaoui *et al.,* 2020).

Additionally, the addition of 0.5 g / L of COD to fruit waste resulted in neutralization of the pH value and improved buffering capacity (dos Santos *et al.,* 2020). Sodium hydroxide can neutralize the pH of lactoserum acid (El Achkar *et al.,* 2020). Furthermore, the mixing method can neutralize the pH value; it passed from 6.84 for meat, 8.51 for fruit and vegetables, and 6.82 for dairy to 7.84 for the mixing together of 33.3% meat + 33.3% fruits and vegetables + 33.3% dairy (Kazimierowicz *et al.,*2021).

2.5.7 Carbon to Nitrogen Ratio C/N

As a critical ratio that can appreciably affect the AD activity (Ajayi-Banji *et al.,* 2020), the carbon to nitrogen ratio (C/N) was established as a feedstock character (Papargyropoulou *et al.,* 2014). Several studies have found that an ideal C/N ratio of 20–30 results in an efficient AD process (Chatterjee and Mazumder, 2019). In a study of the co-digestion of orange bagasse and sewage sludge with a C/N ratio of 30.1 and 5.5, respectively, a high methane accumulation was observed (308 Nml) (dos Santos *et al.,* 2020). Other studies indicated that a ratio of less than 20 was acceptable in the AD system, and Zhang reported that the maximum methane yield (388 mL/g-VS) was achieved in co-digestion of FW and cattle manure at a C/N ratio of 15.8 (Zhang *et al.,* 2013). Furthermore, an optimal methane potential was observed in the co-digestion of dairy manure, chicken manure, and rice straw with Processes 2022, 10, 81 6 of 22 a C/N value of 25:1 for mesophilic reactors and 35:1 for thermophilic reactors (Wang *et al.,* 2014). In a study of co- digestion of meat, fruit and vegetable waste, and dairy waste, the value of 9.77 was the most effective, and the range of operation was from 9.77 to 12.9 (Kazimierowicz *et al.,*2021). A high C/N ratio (high carbon content) caused acidification during the primary stages of the AD process, eventually conducted to process failure (Chatterjee and Mazumder, 2019). The amount of nitrogen was extracted from the breakdown of the proteins throughout the AD reactor, whichis necessary for the growth of microorganisms (Rocamora *et al.,* 2020). A low C/N ratiohighlighted an excessive ammonia concentration, which led to an increase in pH and inhibitory effects, further perturbing the process stability (Drennan and DiStefano, 2014).

2.5.8 Organic Loading Rate (OLR)

The OLR can typically be determined as a kilogram of volatile solid (VS) loaded per digester volume per day and can even be adjusted and regulated to maintain the stability of the AD process (Nasiruddin *et al.,* 2020). Additionally, different critical values are found in the literature. The process could operate at a value of (32 g-VS_{FW}/L + 16 g -VS_{CM}/L) of co- digestion of FW and cattle manure, while the optimum value in this study was 10 g^{-} VSFW/L which increased the methane yield by 55.2% (Zhang *et al.,* 2013). In a study of co-digestion of FW and garden waste, a maximum organic material conversion efficiency of 83% was achieved with an OLR of 0.54 kg VS m^{-3} d^{-1}. When OLR reached 0.63 kgVS/m^3/d the system was perturbed and finally showed some instabilities, such as an increase in VFA concentration (Perin *et al.,* 2020). Moreover, the allowed quantity of OLR was 2.53 kg VS m^{-3} d^{-1} in a thermal pre-treated food waste operated in a semi-continuous reactor under mesophilic conditions (El Gnaoui *et al.,* 2020). Additionally, an OLR value above 6 g ODM dm^{-3} d^{-1} caused an inhibitionof methane fermentation in the co-digestion of meat, dairy, and fruit and vegetables (Kazimierowicz *et al.,* 2021). Furthermore, when the OLR increased, it led to a reduction in biogas productivity and therefore a decrease in the methane content (D¸ebowski *et al.,* 2020). Ina study of anaerobic digestion of mixed supermarket waste under thermophilic conditions, the optimum OLR value was 3.6 kg VS/m3 achieving up to 48.1% more methane production than other OLR values (Megido *et al.,* 2021). At an OLR value of 0.25 Kg m^{-3} d^{-1}, the highest total biogas yield (0.674 m^3 $Kg^{-1}VS$) and methane percentage (62%) were recorded in anaerobic co- digestion of swine manure and corn stover (Arias *et al.,* 2021).

2.5.9 Total Solids Content (TS %)

Generally, the AD process is divided into three ranges based on TS (total solid) percentages, i.e., wet (10%), semi-dry (10–20%), and dry (20%) (Lin *et al.,* 2018). However, these percentages vary in the literature. Dry AD had several limitations, such as the low connection between the microorganisms and substrates, and the accumulation of inhibited matter (VFAs and free ammonia) (Li *et al.,* 2020), which was considered to be related to the high concentration of the solids present in the process (Rocamora *et al.,* 2020). Furthermore, the daily yield of methane production was reduced by 81%, 66%, 23%, and 78% with the augmentation of TS% of 5.49– 20.04% in the mono-digestion of sweet potato vine, pig manure, dairy waste, and chickenmanure, respectively (Zhang *et al.* 2018). In addition, the potential methane yield decreased from 106.3 ml g^{-1} VS^{-1} to 58.5 ml g^{-1} VS^{-1} when TS% was augmented from 5% to 20% in the study of anaerobic digestion of poultry litter (Indren *et al.*, 2020). In the AD of pig manure at a TS content of 25% and above, the pH value was higher than 7.5, which is not the optimum value for methanogen activities (Wang *et al.*, 2020), the specific methane yield was reduced at a TS content of 20% (259.8 NmL g^{-1} $VS^{-1}{}_{added}$) compared to the value recorded in a TS content of 15%(291.7 NmL g^{-1} $VS^{-1}{}_{added}$) (Wang *et al.*, 2020). According to some researchers, wet AD plants have a better energy balance than dry anaerobic digestion plants (Arelli *et al.*, 2018).

The methane yield was higher in the wet AD of chicken manure (0.35 m3/kg VS) compared withthe dry process (0.18 m^3/kg VS) (Bi *et al.*, 2020), furthermore, the methane yield was greater in the wet AD of organic wastes (320 $NLCH_4$ Kg^{-1} VS^{-1}) compared with dry AD (252 $NLCH_4$ Kg^{-1} VS^{-1}) (Di Maria *et al.*, 2017). In contrast, a wet system is commonly used to treat municipal solidwaste in co-digestion with another substrate, among them, animal manure, activated sludge, and sewage sludge.

2.5.10 Volatile Fatty Acid (VFA) Inhibition

In the hydrolysis step, short-chain fatty acids are produced as a result of biodegradable, more complex organic matter such as long-chain fatty acids (LCFAs) and other soluble compounds.

They are popularly known in the literature as volatile fatty acids (VFAs). The main types of VFAs widely found in the hydrolysis stage are acetic, propionic, butyric, and valeric acid(Pramanik *et al.*, 2019). In effect, due to the rapid breakdown of organic matter in the hydrolysis step, a large vast amount of VFA accumulated, resulting in a decrease in the resulting pH value, causing methanogenic inhibition (Shi *et al.*, 2017), which confirmed the strong connectionbetween pH and VFA generation. Besides that, the highest yield of VFA (632.2 mgCOD/g VSf ed) was reported in forced neutral pH, and a minimum yield in alkaline pH (31.4 mgCOD/g VSf ed), in a study of the effect of pH on VFA concentration (65. Lu *et al.*, 2020). Eryildiz realized a maximum VFA yield (0.793 g VFA/VS) when pH was adjusted to 6, and the substrate to inoculum ratio (S/I) was (1:1), whereas low methane generation was observed (Eryildiz and Taherzadeh, 2020). In another study, a maximum reduction of 73.2% and 67.5% in VFA production was reached in the co-digestion of FW and animal fat and vegetable oil batches, respectively (Liu and Jiang, 2020). In addition, Wu et al. discovered that an addition of 6–10% offish residue to waste-activated sludge inhibited the system by the accumulation of VFAs due to the concentration of propionic acid that was indicated to be inhibitory above 1000 mg/L (Wu andSong, 2021, Sun *et al.*, 2019). Another study found that a VFA concentration range of 50 to 250 mg/L was ideal for excellent performance of the anaerobic digester (Ren *et al., 2018*). As a solution to the exceeded VFA generation, an increase in inoculum to substrate ratio (I/S) was frequently applied for batch processes (Rocamora *et al.*, 2020). Despite this, many published studies prefer to stop the AD process in VFA production due to the high valorisation of the primary VFA acids and their significant prices (Eryildiz and Taherzadeh, 2020). Additionally, monitoring

VFA concentrations has a significant effect on the avoidance of negative results. Actually, more advanced techniques have been developed to accurately track the efficiency of the reactor, including online monitoring-based GC, and titration (Kumar and Samadder, 2020). Processes 2022, 10, 81 8 of 22.

2.5.11 Ammonia Inhibition

Nitrogen as a by-product of proteins is considered the main source for microbial growth. Furthermore, the distribution of nitrogen is necessary to the AD process because a high concentration of ammonia nitrogen leads to AD-process inhibition (Li *et al.*, 2020). Additionally,in digesters, it can act as a natural buffer that helps tolerate acidification (Yuan and Zhu, 2016). Meanwhile, it exists in two major forms in the AD process: ammonium ions (NH+4), and free ammonia commonly noted as (FA), that last one is more toxic than the ion form (Altinbas and Cicek, 2019). It is capable of penetrating the bacterial cell membrane, producing proton imbalances, raising maintenance energy needs, and blocking certain enzyme responses (Akindeleand Sartaj, 2018). In addition, ammonia concentration is linked directly to the pH value and operating temperature. It increases with the temperature and pH; a concentration of FA of 600 mg-N/L can inhibit the system under thermophilic conditions. However, different studies reported different critical ammonia concentration ranges: free ammonia generally has inhibitory values ranging from 300 mg/L to 800 mg/L, whereas ammonium is tolerated at higher concentrations ranging from 1500 to 3000 mg/L (Rocamora *et al.*, 2020). The concentration of ammonia in a co-digestion of FW and cattle manure was less than the critical value of 700 mg/L under semi-continuous mesophilic conditions.

In contrast, in a mono-digestion of cattle dung, the value was exceeded (Zhang *et al.*, 2013). A considerable value of ammonia above 380 mg/kg led to a diminution of methane production of between 22% and 55% in the mono-digestion of pig manure, chicken manure, and co-digestionof sweet potato vine and chicken dung under dry conditions (Zhang *et al.* 2018). Thus, ammonia concentration has to be adequately controlled and monitored during the AD operation to avoid a toxic concentration that can allegedly lead to inhibition of the microbial community.

2.6 The Effect of Co-Digestion, Pre-treatment Methods, and Mixing Techniques on theAD Process

2.6.1 Effect of Co-Digestion in the AD System

Typically, anaerobic co-digestion is defined as a strategy of mixing two or more substrates for simultaneous processing. This technique has been applied to overcome the potential limitations and problems of the mono-digestion process, such as system instability due to inhibitory factors, low methane yield caused by mono substrate characteristics (a notable example is FW, known for high carbon content, low alkalinity, high organic loads, and low nitrogen content) (Pramanik *et al.*, 2019, Mehariya *et al.*, 2018). Numerous studies have supported anaerobic co-digestion of different feedstocks due to the numerous specific benefits that can be generated, such as good buffering capacity and process stability support by diluting inhibitory concentrations (Capson- Tojo *et al.*, 2017), leading to methane yield enhancement. Furthermore, animal manure, sewage sludge, and lignocellulosic wastes are the most adequate co-substrates that can be utilized in the anaerobic co-digestion of FW due to their high ammonia content, intense alkalinity, and other specifications that can balance the process nutrients and the AD operation (Pramanik *et al.,* 2019). Furthermore, Zhang et al. reported that methane productivity increased by 41.1% and reached a maximum value of 3725 ml compared to mono digestion 2624 mL; thereby an optimal C/N ratio (15.8) and neutral pH were obtained, the concentrations of essential trace elements were improved, which had a significant effect in encouraging methanogen activities, and the process worked at a high OLR value (Zhang *et al.,* 2013). Oladipupo et al. indicated a decreaseof 57% in chemical oxygen demand (COD, which is the amount of oxygen required to oxidize anorganic compound to CO_2, ammonia and water) in a co-digestion of FW and piggery dung (PD);and a maximum value of biogas, a high mass equilibrium (0.38), and the most consumed rate of volatile solid (VS) (48%) were achieved with a high percentage of methane (63%) in a co- digestion of FW, PD and cow dung compared to mono-digestion of FW (Oladejo *et al.,* 2020) Further, a proper co-digestion of 20% (OLR) of garden waste and FW conserved the pH at a neutral value, and VFA concentrations were in the optimum range. There was also a reduction in VS by 83% and a high methane percentage (67%) was obtained in the co-digestion process (Perin *et al.,* 2020). On the other hand, the quantity of co-substrate added should be controlled, which was confirmed in a co-digestion of waste-activated sludge and fish waste: the addition of 6% or more of fish waste reduced processes 2022, 10, 81 9 of 22 methane production toapproximately (51 ml CH_4 / g VS) and inhibited the process by accumulation of VFA and LCFA, while the addition of 3% of fish waste maximized methane production (683.8 ml CH_4 / g VS) (Wu and Song, 2021).

2.6.2 Effect of Pre-treatment Techniques in the AD System

The AD process has critical drawbacks due to its complexity and inhibitory factors. Among the adequate solutions that improve the process by increasing the rate of decomposition of the organic fraction and the generation of methane, otherwise improving the efficiency of theprocess, is the application of pre-treatment methods (Kainthola *et al.,* 2019). We distinguish a variety of techniques depending on the process used. Therefore, we have chemical, physical, biological and combined techniques (Atelge *et al.,* 2020). In fact, the choice of a more suitable method depends on its mechanism, substrate properties, and final requirements (Kumar and Samadder, 2020). Various pre-treatment techniques have been reported in the literature recently, to maintain process stability as a chemical pre-treatment. An addition of (0.5 g NaHO3 g^{-1} COD^{-1}) sodium bicarbonate kept the pH value at neutral (dos Santos *et al.*, 2020), 3 M HCL and 3 M NaOH adjusted the pH value (Wu and Song, 2021), NaOH neutralized the pH of lactoserum acid (El Achkar *et al.*, 2020). Moreover, an addition of salt (6 g/L) augmented the maximum VFA production by 14% (23.11 g/L) more than without salt (19.86 g/L), and alleviated inhibition caused by animal fats and vegetable oils (Liu and Jiang, 2020). The extraction of the inhibitor D-limonene from the orange peel by 70% in one hour was achieved by using steam distillation, which increased the biodegradability to 96.7% in COD in the thermophilic AD of orange peel (Martín *et al.*, 2018). While, physical pre-treatment such as thermal techniques had severalbenefits, in the anaerobic digestion of swine manure, the methane production rate was enhanced by 390% (Hu *et al.*, 2019). In a study conducted by El Gnaoui et al., thermal pre-treatment of FW at 100°C for 30 min raised soluble COD by 43.41%, the methane yield was enhanced by 23.68%,and the biodegradability was increased by 9.8% compared with the untreated FW (El Gnaoui *et al.*, 2020). In another study, thermal pre-treatment of kitchen waste produced a high hydrogen rate of up to 113 mL H2/g VS_{fed} (Gallipoli *et al.*, 2020). On the other hand, an intensification in methane production was observed in the application of energy of 90 KJ/KG during an ultrasound pre-treatment on the inoculum presented by cow manure in the treatment of dairy waste (El Achkar *et al.*, 2020). The development of resilient microbiomes that can be acclimatized under thermophilic temperatures and resist the inhibitory concentrations by adjusting the substrate: inoculum ratio is one of the conventional pre-treatments. Ghanimeh et al. indicated that by inoculating (digestate, manure, and activated sludge) thermophilic anaerobic digesters during the loading period, the pH decreased to 7.2 and gradually increased to stabilize at 7.8, confirming the acclimation of microbial flora (Ghanimeh *et al.*, 2018). Elsewhere, the co-digestion of different substrates has also been reported as a conventional pre-treatment method, which can be implemented without any major modification in the system. In contrast, in the literature, emerging pre-treatment methods have been reported: for example, the integration of microbial electrochemical systems to combine the microbial metabolism of electro-active bacteria with electro-chemistry; and the application of conductive additives so that electro-active bacteria directly transfer electrons to methanogens and reduce CO_2 to CH_4 in order to augment methane production and biogas quality. However, these techniques need a change in the process (Ryue *et al.*, 2020).

2.6.3 Effect of Mixing Methods on the AD Process

Mixing is one of the methods that can influence AD efficiency because it keeps microbes in contact with the substrate, promotes uniform conditions throughout the digester volume, and improves process kinetics and methane production (Rocamora *et al.*, 2020). It was found that reactors without any mixing failed with propionic acid inhibition (Wang *et al., 2020*), the production of CH_4 with mixing pre-treatment was higher (75 L CH_4 Kg^{-1} VS^{-1}) than that without mixing pre-treatment (60 L CH_4 Kg^{-1} VS^{-1}) in psychrophilic AD of swine manure slurry (Massé et al.,1996)

Moreover, there are three types of mixing: Gas recirculation (Vesvikar *et al.*, 2005), slurry recirculation (Rico *et al.*, 2011), and mechanical (impeller) mixing (Kariyama *et al.*, 2018). It is critical to select the proper mixing technique to achieve efficient mixing and maximum biogas production while consuming the least Processes 2022, 10, 81 10 of 22 amount of energy. Digesters fed with 10% manure slurry and mixed using biogas recirculation, slurry recirculation, and impeller produced 15%, 29%, and 22% more biogas than unmixed digesters in AD of animalmanure (Karim *et al.*, 2005). Mechanical mixing is the most frequently utilized method and has been estimated to have the best power efficiency per volume unit mixed (Lindmark *et al.*, 2014). In general, there are two modes of mixing; intermittent and continuous mode (Lindmark *et al.*, 2014). A high specific methane yield was achieved (437 mL CH_4 g^{-1} $VS^{-1}{}_{fed}$) in intermittent mixed reactors (2 min/h) compared to continuously and non-mixed reactors in the AD of FW (Zhang *et al.*, 2019). An increase in biogas production by 7% was achieved with intermittent mixing compared to continuous mixing (Kaparaju *et al.*, 2008). Therefore, it is considered an alternative strategy to reduce energy consumption. On the other hand, intense mixing strategies are known to have negative effects (Rocamora *et al.*, 2020). High shear forces can destroy microbial flocs and syntrophic interactions between methanogens and bacteria during start-up or high-load periods, resulting in negative impacts (Singh *et al.*, 2019). The cumulative biogas production at a mixing intensity of 80 rpm was higher by 18.3% compared to a mixing intensity of 160 rpm (Shen *et al.*, 2013). Household Waste Generation.

2.7 Household Waste Generation

Knowledge of waste generation rate, types of wastes generated, generation rate per income level and types of wastes generated per income level as well as generation rates during weekdays and weekends can help in planning for solid waste management system. Both physical and chemical composition of the wastes can help in determining the energy value of the wastes hence the possibility of the wastes as energy sources. Human activities create wastes which need handling, storage, collection and disposal as they pose risk to the environment and public health (Gupta *et al.*, 2015). Economic growth, industrialization and improved living standards in cities across the world have been reported as factors that have contributed to increased solid wastes generationand challenges associated with management of solid wastes (Vitorino de Souza Melaré *et al.*, 2017). Solid wastes generated should be managed accordingly in a systematic engineered approach. However, studies have reported poor waste management especially in developing countries. For instance (Gupta *et al.*, 2015) reported that poor collection and inadequate transportation contribute to the accumulation of wastes in many cities. It has been reported that most of the municipal solid wastes are generated from households (55% to 80%) and 10% to30% from commercial areas (Miezah *et al.*, 2015). These wastes are heterogeneous in nature and vary in physical characteristics depending on their sources. The heterogeneity is a disadvantage as wastes have to be separated for recycling to be achieved (Miezah *et al.*, 2015).

The composition of the solid wastes depends on a number of factors such as food habits, cultural traditions, climate and income (Gupta *et al.*, 2015). Municipal solid waste management involves a collection of stages namely generation, storage, separation, collection, energy recovery and disposal activities. Generation of solid wastes depends on factors such as social behaviour, income level, sources, population, climate, industrial production and market for waste materials (Gupta *et al.*, 2015). Miezah *et al. (2015),* who conducted a study on the characterisation and quantification of municipal solid waste as a measure of effective waste management in Ghana, found that the average generation rates in ten regional capitals were 0.51 kg/person/day and 0.47 kg/person/day for areas outside of the regional capitals. The generation rate was attributed to location in the district, geographic location, income and household size. Knowing the amount and composition of wastes generated is important for the planning, operation and optimisation of waste management systems (Dehghanifard and Dehghani, 2018). Poor waste collection organisation has been reported, for example, in India, with poor storage at the source and poor design of collection bins leading to poor collection efficiency (Gupta *et al.,* 2015). Emphasis is now on material recovery and utilisation of some of the wastes as a source of energy.

Transportation has been identified as one of the factors that contribute to inadequate solid waste management (Yukalang *et al.,* 2017). Failure to collect and transport solid wastes has in most cases resulted in rodents and dogs vandalising storage facilities therefore wastes scattered over streets. Some cases have been reported where wastes disposal sites are inadequate to serve the user population as the volume of the generated solid wastes is overwhelming (Yoada *et al.,* 2014). Some wastes are disposed of at dumping sites instead of engineered landfills or other disposal facilities such as incinerators. Disposal of wastes in India has been reported to be lacking and in most cases composting, waste to energy being the main disposal methods (Gupta*et al.,* 2015). It has been reported that poor waste management situation has led to high incidences of sanitation related illnesses such as cholera, intestinal worms and typhoid (Yoada *et al.,* 2014)

2.8 Dimensioning of biodigester

For a biodigester to be dimensioned, various parameters to be set are the HRT, the availability of feedstock and the required cooking time. Here the amount of feedstock available was used as the main parameter to dimension the biodigester instead of the cooking time required. Furthermore, it was assumed that the amount of biogas produced with the available feedstock could cover or slightly not less than the required cooking time. However, assuming that the average available feedstock is about 30kg per day of fresh manure (three cows) and it will be mixed with about

30 litres of water in the proportion of 1:1, the daily inlet volume can be set equal to 60L. This value, considering cow dung, correspond to 0.5kg VVS/day. HRT for the local condition is about 20days for an average temperature of 28 degrees. Therefore, the biodigester volume can be calculated using the following equation (Jorgensen, 2009)

$VD(l) = Sd(l/day)\ x\ HRT\ (days)$

Where, Vd is the Volume of the biodigester.

Sd is the amount of feedstock added per day (l/day)

HRT is the Hydraulic retention time (day).

Once the biodigester volume is calculated, it is important to evaluate the required gas holder size, which seems to be one of the important planning parameters in the dimensioning of the biodigester

2.9 Composition of organic waste collected

The food (kitchen waste) was collected in the four buckets provided to the canteen of SWMTSC.Composition of the collected waste was identified by visual estimation. With the help of the eyes, the composition of the waste was identified and categorized according to its amount present in the collected waste.

2.10 Sampling of waste and slurry sample

For the representative waste sample, 50 g of waste, each from four buckets, was kept togetherand mixed. This sample was air dried, ground, and sieved. Thus, prepared waste sample was used for laboratory analysis. The bio-slurry was also air dried, ground, and sieved. This sample was used for laboratory analysis.

2.11 Factors that Affect Solid Waste Characteristics

Family Size. The size of the family is an important component in determining the amount of household waste. In this research, family size refers to the general number of people living in the same house. Previous studies (Khan *et al.*, 2016, Trang *et al.*, 2017, Sankoh *et al.*, 2012 Senzige *et al.*, 2014 Sujauddin *et al.*, 2008) showed that household size had a positive influence on the waste generation rate. While it is apparent that more members of a family generate more waste, some researchers described the phenomena of 'group living' and 'common consumption' of the family as the household operates as a unit and most food items are shared. Therefore, the smaller the amount of food crumbs, leftovers and packaging waste will be produced (Ojeda- Ben´ıtez *et al.*, 2008). On the contrary, many studies have also supported the negative relationship between household size and waste generation rate (Miezah *et al.*, 2015; Qu *et al.*, 2009; Thanh *et al.*, 2010) that household size had a positive influence on waste generation rate and it is apparent that more members of a family generate more waste. Furthermore, a bivariate statistical analysis method of bivariate analysis (Pearson's coefficient) was used to test the correlation between household waste generation and household size. In the present study, a medium positive correlation composition of waste generated due to changes in the consumption pattern of households (Ogwueleka, 2013). Many research studies (Philippe and Culot, 2009, Thanh *et al.*, 2010 Sankoh *et al.*, 2012, Sujauddin *et al.*, 2008, Ogwueleka, 2013, supported the idea that the household income has a direct and positive relationship with the daily per capita waste generation. As per those studies, the higher the income of a household, the higher its purchasing power, and this can be the reason for income being a positive impact on the amountof waste. On the contrary, Qu *et al.*, (2009) found that family income has a negative impact on the waste generation rate. Also, Trang *et al.*, (2017) indicated that higher-income households prefer to eat outside more frequently than cooking at home, thereby generating less waste.

2.12 Waste Treatment and Disposal Methods

When people think about solid waste management, they likely associate it with garbage being dumped in landfills or incinerated. While such activities comprise an important part of the process, a variety of elements is involved in the creation of an optimal integrated solid waste management (ISWM) system. For example, treatment techniques act to reduce the volume and toxicity of solid waste. These steps can transform it into a more convenient form for disposal. Waste treatment and disposal methods are selected and used based on the form, composition, andquantity of waste materials (Rick, 2019).

2.13 Major waste treatment and disposal methods:

2.13.1 Thermal Treatment

Thermal waste treatment refers to the processes that use heat to treat waste materials. Following are some of the most commonly used thermal waste treatment techniques:

Incineration is one of the most common waste treatments. This approach involves the combustion of waste material in the presence of oxygen. This thermal treatment method is commonly used as a means to recover energy for electricity or heating. This approach has severaladvantages. It quickly reduces waste volume, lessens transportation costs and decreases harmful greenhouse gas emissions.

Gasification and Pyrolysis are two similar methods, both of which decompose organic waste materials by exposing waste to low amounts of oxygen and very high temperature. Pyrolysis usesabsolutely no oxygen while gasification allows a very low amount of oxygen in the process. Gasification is more advantageous as it allows the burning process to recover energy without causing air pollution.

Open Burning is a legacy thermal waste treatment that is environmentally harmful. The incinerators used in such process have no pollution control devices. They release substances suchas hexachlorobenzene, dioxins, carbon monoxide, particulate matter, volatile organic compounds, polycyclic aromatic compounds, and ash. Unfortunately, this method is still practiced by many local authorities internationally, as it offers an inexpensive solution to solid waste.

2.13.2 Dumps and Landfills

Sanitary landfills provide the most commonly used waste disposal solution. These landfills are desired to eliminate or reduce the risk of environmental or public health hazards due to waste disposal. These sites are located where the land features act as natural buffers between theenvironment and the landfill. For example, the landfill area can consist of clay soil that is quite resistant to hazardous waste or characterized by the absence of surface water bodies ora low water table, preventing the risk of water pollution (Trang *et al.*, 2017).

The use of sanitary landfills poses the least health and environmental risk, but the cost of establishing such landfills is comparatively higher than other waste disposal methods.

Controlled dumps are more or less the same as sanitary landfills. These dumps comply with many of the requirements for being a sanitary landfill but may lack one or two. Such dumps may have a well-planned capacity but no cell-planning. There may be no or partial gas management, basic record keeping, or regular cover.

Bioreactor landfills are the result of recent technological research. These landfills use superior microbiological processes to speed up waste decomposition. The controlling feature is the continuous addition of liquid to sustain optimal moisture for microbial digestion. The liquid is added by re-circulating the landfill leachate. When the amount of leachate is not adequate, liquid waste such as sewage sludge is used.

2.13.3 Biological Waste Treatment

Composting is another most frequently used waste disposal or treatment method which is the controlled aerobic decomposition of organic waste materials by the action of small invertebrates and microorganisms. The most common composting techniques include static pile composting, vermin-composting, windrow composting and in-vessel composting (Trang *et al.*, 2017).

Anaerobic Digestion also uses biological processes to decompose organic materials. Anaerobic digestion, however, uses an oxygen and bacteria-free environment to decompose the waste material where composting must have air to allow microbe growth (Trang *et al.*, 2017).

2.14 Climate Change

2.14.1 Global Warming

The Earth is warming up, and humans are at least partially to blame. The causes, effects, and complexities of global warming are important to understand so that we can fight for the health ofour planet (NGS, 2020).

Global warming is the long-term warming of the overall temperature of the planet. Although this warming trend has been going on for a long time, its pace has increased significantly in the last 100 years due to the burning of fossil fuels (NGS, 2020). As the human population has increased, so has the volume of fossil fuels burn. Fossil fuels include coal, oil, and natural gas, and burning them causes what is known as the –greenhouse effect‖ in Earth's atmosphere (NGS, 2020).

Global warming has presented another issue called climate change. Sometimes these phrases are used interchangeably, however, they are different (NGS, 2020). Climate change refers to changesin weather patterns and growing seasons around the world. It also refers to the rise in sea level caused by the expansion of warmer seas and the melting of ice sheets and glaciers. Global warming causes climate change, which poses a serious threat to life on earth in the forms of widespread flooding and extreme weather. Scientists continue to study global warming and its impact on Earth (NGS, 2020).

Global warming, the phenomenon of increasing average air temperatures near the surface ofEarth over the past one to two centuries (UNEP, 2021). Climate scientists have since the mid- 20th century collected detailed observations of various weather phenomena (such as temperatures, precipitation, and storms) and related influences on climate (such as ocean currents and the chemical composition). These data indicate that Earth's climatehas changed over almost every conceivable timescale since the beginning of geologic time and that human activities since at least the beginning of the Industrial Revolution have a growing influence over the pace and extent of present-day climate change (UNEP, 2021).

Giving voice to a growing conviction of most of the scientific community, the

IntergovernmentalPanel on Climate Change (IPCC) was formed in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). The IPCC's Sixth Assessment Report (AR6), published in 2021, noted that the best estimate of the increase in global average surface temperature between 1850 and 2019 was 1.07 °C (1.9 °F). An IPCC special report produced in 2018 noted that human beings and their activities have been responsible for a worldwide average temperature increase between 0.8 and 1.2 °C (1.4 and 2.2 °F) since preindustrial times, and most of the warming over the second half of the 20th century could be attributed to human activities (Michael, 2022).

Many climate scientists agree that significant societal, economic, and ecological damage would result if the global average temperature rose by more than 2 °C (3.6 °F) in such a short time.Such damage would include increased extinction of many plant and animal species, changes in agricultural patterns, and rising sea levels. By 2015 all but a few national governments had begun the process of instituting carbon reduction plans as part of the Paris Agreement, a treaty designed to help countries keep global warming to 1.5 °C (2.7 °F) above preindustrial levels in order to avoid the worst of the predicted effects. Although, the authors of the 2018 special reportnoted that should carbon emissions continue at their current rate, the increase in average near- surface air temperature would reach 1.5 °C sometime between 2030 and 2052, the authors of theAR6 report suggested that this threshold would be reached by 2041 at the latest (Michael, 2022).

The AR6 report also noted that the global average sea level had risen by some 20 cm (7.9 inches)between 1901 and 2018 and that sea level rose faster in the second half of the 20th century thanin the first half. It also predicted, again depending on a wide range of scenarios, that the global average sea level would rise by different amounts by 2100 relative to the 1995–2014 average. Under the lowest-emission scenario of the report, the sea level would rise by 28 to55 cm (11–21.7 inches), while, under the intermediate emissions scenario, the sea level would rise by 44 to 76 cm (17.3–29.9 inches). The highest-emissions scenario suggested that sea level would rise by 63 to 101 cm (24.8–39.8 inches) by 2100 (Michael, 2022).

The scenarios referred to above depend mainly on future concentrations of certain trace gases, called greenhouse gases that have been injected into the lower atmosphere in increasing amounts through the burning of fossil fuels for industry, transportation, and residential uses (Michael, 2022). Modern global warming is the result of an increase in the magnitude of the so-called greenhouse effect, a warming of the Earth's surface and lower atmosphere caused by the presence ofwater vapour, carbon dioxide, methane, nitrous oxides, and other greenhouse gases. In 2014 the IPCC first reported that concentrations of carbon dioxide, methane, and nitrous oxides in the atmosphere surpassed those found in ice cores dating back 800,000 years 90 (Michael, 2022).

2.14.2 Greenhouse Effect on Earth

Some incoming sunlight is reflected by Earth's atmosphere and surface, but most is absorbed by the surface, which is warmed. Infrared (IR) radiation is then emitted from the surface. Some IR radiation escapes to space, but some is absorbed by the atmosphere's greenhouse gases (especially water vapour, carbon dioxide, and methane) and reradiated in all directions, some to space and some back toward the surface, where it further warms the surface and the lower atmosphere (Michael, 2022). Of all these gases, carbon dioxide is the most important, because of itsrole in the greenhouse effect and because of its role in the human economy. It has been estimated that, at the beginning of the industrial age in the mid-18th century, carbon dioxide concentrations in the atmosphere were roughly 280 parts per million (ppm). By the end of 2021 they had risen to 416 ppm, and, if fossil fuels continue to be burned at current rates, they are projected to reach 550 ppm by the mid-21st century—essentially, a doubling of carbon dioxide concentrations in 300 years (Michael, 2022).

2.14.3 Greenhouse Gases

Gases that trap heat in the atmosphere are called greenhouse gases. This section provides information on emissions and removals of the main greenhouse gases to and from the atmosphere (IPCC, 2013).

Carbon dioxide (CO_2): Carbon dioxide enters the atmosphere through burning fossil fuels (coal, natural gas, and oil), solid waste, trees and other biological materials, and also as a result of certain chemical reactions (e.g., manufacture of cement). Carbon dioxide is removed from the atmosphere (or "sequestered") when it is absorbed by plants as part of the biological carbon cycle(IPCC, 2013).

Methane (CH_4): Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices, land use and by the decay of organic waste in municipal solid waste landfills (IPCC, 2007).

Nitrous oxide (N_2O): Nitrous oxide is emitted during agricultural, land use, and industrialactivities; combustion of fossil fuels and solid waste; and during wastewater treatment (1IPCC, 2007).

Fluorinated gases: Hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, and nitrogen trifluoride are synthetic, powerful greenhouse gases that are emitted from a variety of household,commercial, and industrial applications and processes (IPCC, 2007). Fluorinated gases (especially hydrofluorocarbons) are sometimes used as substitutes for stratospheric ozone- depleting substances (e.g., chlorofluorocarbons, hydrochlorofluorocarbons, and halons). Fluorinated gases are typically emitted in smaller quantities than other greenhouse gases, butthey are potent greenhouse gases. With global warming potentials (GWPs) that typically range from thousands to tens of thousands, they are sometimes referred to as high-GWP gases because,for a given amount of mass, they trap substantially more heat than CO_2 (IPCC, 2007).

The effect of each gas on climate change depends on three main factors: Concentration, or abundance, is the amount of a particular gas in the air. Larger emissions of greenhouse gases lead to higher concentrations in the atmosphere. Greenhouse gas concentrations are measured in parts per million, parts per billion, and even parts per trillion. One part per million is equivalent to one drop of water diluted into about 13 gallons of liquid (roughly the fuel tank of a compact car) (IPCC, 2007).

Each of these gases can remain in the atmosphere for different amounts of time, ranging from a few years to thousands of years. All of these gases remain in the atmosphere long enough to become well mixed, which means that the amount measured in the atmosphere is roughly the same throughout the world, regardless of the source of the emissions.

Some gases are more effective than others at making the planet warmer and "thickening the Earth's blanket. For each greenhouse gas, a Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). Gases with a higher GWP absorbmore energy, per pound emitted, than gases with a lower GWP, and thus contribute more to warming Earth.

Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities. In 2020, CO_2 accounted for about 79% of all U.S. greenhouse gas emissions from human activities. Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon among the atmosphere, oceans, soil, plants, and animals). Human activities are altering the carbon cycle–both by adding more CO_2 to the atmosphere and by influencing the ability of natural sinks, like forests and soils, to remove and store CO_2 from the atmosphere. While CO_2 emissions come from a variety of natural sources, human-related emissions are responsible for the increase that has occurred in the atmosphere since the industrialrevolution.

The main human activity that emits CO_2 is the combustion of fossil fuels (coal, natural gas, and oil) for energy and transportation. Certain industrial processes and land-use changes also emit CO_2. The main sources of CO_2 emissions in the United States are described below.

2.14.4 Transportation

The combustion of fossil fuels such as gasoline and diesel to transport people and goods was the largest source of CO_2 emissions in 2020, accounting for about 33% of total U.S. CO_2 emissions and 26% of total U.S. greenhouse gas emissions. This category includes domestic transportation sources such as highway and passenger vehicles, air travel, marinetransportation, and rail.

2.14.5 Electricity

Electricity is a significant source of energy in the United States and is used to power homes, business, and industry. In 2020, the combustion of fossil fuels to generate electricity was the second largest source of CO_2 emissions in the nation, accounting for about 31% of total U.S.CO_2 emissions and 24% of total U.S. greenhouse gas emissions. The types of fossil fuel used to generate electricity emit different amounts of CO_2. To produce a given amount of electricity, burning coal will produce more CO_2 than natural gas or oil.

2.14.6 Industry.

Many industrial processes emit CO_2 through fossil fuel consumption. Several processes also produce CO_2 emissions through chemical reactions that do not involve combustion, and examples include the production of mineral products such as cement, the production of metals such as iron and steel, and the production of chemicals. Carbon dioxide is constantly being exchanged among the atmosphere, ocean, and land surface as it is both produced and absorbed by many microorganisms, plants, and animals. However, emissions and CO_2 removal by these natural processes, tend to balance out, absent anthropogenic impacts. Since the Industrial Revolution began around 1750, human activities have contributed substantially to climate changeby adding CO_2 and other heat-trapping gases to the atmosphere.

In the United States, the management of forests and other land (e.g., cropland, grasslands, etc.) has acted as a net sink of CO_2, which means that more CO_2 is removed from the atmosphere, andstored in plants and trees, than is emitted. This carbon sink offset is about 14% of total emissionsin 2020 and is discussed in more detail in the Land Use, Land-Use Change, and Forestry section.

To find out more about the role of CO_2 in warming the atmosphere and its sources, visit the Climate Change Indicators page.

2.14.7 Emissions and Trends

Carbon dioxide emissions in the United States decreased by about 8% between 1990 and 2020. Since the combustion of fossil fuel is the largest source of greenhouse gas emissions in the United States, changes in emissions from fossil fuel combustion have historically been the dominant factor affecting total U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population growth, economic growth, changing energy prices, new technologies, changing behaviour, and seasonal temperatures. In 2020, the decrease in CO_2 emissions from fossil fuel combustion corresponded with a decrease in energy use as a result of decreases in economic, manufacturing, and travel activity in response to the coronavirus pandemic, in addition to a continued shift from coal to less carbon-intensive natural gas and renewables in the electric power sector.

2.14.8 Energy Conservation

Reducing personal energy use by turning off lights and electronics when not in use reduces electricity demand. Reducing distance travelled in vehicles reduces petroleum consumption. Bothare ways to reduce energy CO_2 emissions through conservation. Fuel Switching Producing moreenergy from renewable sources and using fuels with lower carbon contents are ways to reduce carbon emissions

2.15 Carbon Capture and Sequestration (CCS)

Carbon dioxide capture and sequestration is a set of technologies that can potentially greatly reduce CO_2 emissions from new and existing coal- and gas-fired power plants, industrial processes, and other stationary sources of CO_2 (IPCC, 2013). For example, a CCS project could capture CO_2 from the stacks of a coal-fired power plant before it enters the atmosphere, transportthe CO_2 via a pipeline, and inject the CO_2 deep underground in a carefully selected and suitable subsurface geologic formation, such as a nearby abandoned oil field, where it is stored securely (IPCC, 2013).

Atmospheric CO_2 is part of the global carbon cycle, and therefore its fate is a complex functionof geochemical and biological processes (IPCC, 2013). Some of the excess carbon dioxide willbe absorbed quickly (for example, by the ocean surface), but some will remain in the atmospherefor thousands of years, due in part to the very slow process by which carbon is transferred to ocean sediments (IPCC, 2013).

In 2020, methane (CH_4) represented approximately 11% of all greenhouse gas emissions from human activities in the United States (IPCC, 2013). Human activities that emit methane include leaks from natural gas systems and the raising of livestock. Methane is also emitted by natural sources such as natural wetlands. Furthermore, natural processes in the soil and chemical reactions in the atmosphere help remove CH_4 from the atmosphere. The lifetime of methane in the atmosphere is much shorter than that of carbon dioxide (CO2), but CH_4 is more efficient in trapping radiation than CO_2. Pound for pound, the comparative impact of CH_4 is 25 times greater than CO_2 over a 100-year period (IPCC, 2013).

2.16 Reducing Methane Emissions

There are a number of ways to reduce CH_4 emissions. Some examples are discussed below. EPA has a series of voluntary programs for reducing CH_4 emissions, in addition to regulatory initiatives. EPA also supports the Global Methane Initiative, an international partnership encouraging global methane reduction strategies (Saunois *et al.*, 2020).

2.17 Examples of Reduction Opportunities for Methane industry

Upgrading the equipment used to produce, store, and transport oil and natural gas can reduce many of the leaks that contribute to CH_4 emissions. Methane from coal mines can also be captured and used for energy. Learn more about the EPA's Natural Gas STAR Program and Coalbed Methane Outreach Program.

2.17.1 Agriculture

Methane from manure management practices can be reduced and captured by altering manure management strategies. Additionally, modifications to animal feeding practices may reduceemissions from enteric fermentation. Learn more about improved manure management practices at EPA's AgSTAR Program (Saunois *et al.*, 2020).

2.17.2 Waste from Homes and Businesses

Because CH_4 emissions from landfill gas are a major source of CH_4 emissions in the United States, emission controls that capture landfill CH_4 are an effective reduction strategy. Learn moreabout these opportunities and the EPA's Landfill Methane Outreach Program (Saunois *et al.*, 2020).

Human activities such as agriculture, fuel combustion, wastewater management, and industrial processes are increasing the amount of N_2O in the atmosphere. Nitrous oxide is also naturally present in the atmosphere as part of the Earth's nitrogen cycle and has a variety of natural sources. Nitrous oxide molecules stay in the atmosphere for an average of 114 years before beingremoved by a sink or destroyed through chemical reactions. The impact of 1 pound of N2O on warming the atmosphere is almost 300 times that of 1 pound of carbon dioxide (EPA, 2005).

Agriculture. Nitrous oxide can result from various agricultural soil management activities, suchas application of synthetic and organic fertilizers and other cropping practices, the managementof manure, or burning of agricultural residues (EPA, 2005). Agricultural soil management is the largest source of N_2O emissions in the United States, accounting for about 74% of total U.S. N_2Oemissions in 2020. Although not shown in the figure and less significant, N2O emissions also occur as a result of land use and land management activities in the Land Use, Land Use Change and Forestry sector (e.g. forest and grassland fires, application of synthetic nitrogen fertilizers to urban soils (e.g., lawns, golf courses) and forest land, etc.).

Fuel Combustion. Nitrous oxide is emitted when fuels are burned. The amount of N_2O emitted from burning fuels depends on the type of fuel and combustion technology, maintenance, and operating practices.

Industry. Nitrous oxide is generated as a by-product during the production of chemicals such as nitric acid, which is used to make synthetic commercial fertilizers, and in the production of adipic acid, which is used to make fibres, such as nylon and other synthetic products.

Waste. Nitrous oxide is also generated from treatment of domestic wastewater during nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, andproteins.

Nitrous oxide emissions occur naturally through many sources associated with the nitrogen cycle, which is the natural circulation of nitrogen among the atmosphere, plants, animals, and microorganisms that live in soil and water. Nitrogen takes on a variety of chemical forms throughout the nitrogen cycle, including N_2O. Natural emissions of N2O are mainly frombacteria breaking down nitrogen in soils and the oceans. Nitrous oxide is removed from the atmosphere when it is absorbed by certain types of bacteria or destroyed by ultraviolet radiation or chemical reactions (IPCC, 2013).

2.17.3 Reducing Nitrous Oxide Emissions

Agriculture

The application of nitrogen fertilizers accounts for the majority of N_2O emissions in the United States. Emissions can be reduced by reducing nitrogen-based fertilizer applications and applying these fertilizers more efficiently, as well as modifying a farm's manure management practices (EPA, 2005).

2.17.4 Fuel Combustion

Nitrous oxide is a by-product of fuel combustion, so reducing fuel consumption in motor vehicles and secondary sources can reduce emissions. Additionally, the introduction of pollution control technologies (e.g., catalytic converters to reduce exhaust pollutants from passenger cars) can alsoreduce emissions of N_2O (EPA, 2005).

2.17.5 Industry

Nitrous oxide is generally emitted from industry through fossil fuel combustion, so technological upgrades and fuel switching are effective ways to reduce industry emissions of N_2O. Production of nitric acid and adipic acid result in N_2O emissions that can be reduced through technological upgrades and use of abatement equipment (EPA, 2005).

2.17.6 Global warming potential

Greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which theenergy escapes to space; they act like a blanket insulating the Earth (USEPA, 2022). Different GHGs can have different effects on the Earth's warming. Two key ways in which these gases differ from each other are their ability to absorb energy (their "radiative efficiency"), and how long they stay in the atmosphere (also known as their "lifetime").

The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases (USEPA, 2022). Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory), and allows policymakers to compare emissions reduction opportunities across sectors and gases (USEPA, 2022).

CO_2, by definition, has a GWP of 1 regardless of the time period used, because it is the gas beingused as the reference. CO_2 remains in the climate system for a very long time: CO_2 emissions.

cause increases in atmospheric concentrations of CO_2 that will last thousands of years (USEPA, 2022).

Methane (CH_4) is estimated to have a GWP of 27-30 over 100 years (Learn why EPA's U.S. Inventory of Greenhouse Gas Emissions and Sinks uses a different value.). CH_4 emitted today lasts about a decade on average, which is much less time than CO_2. But CH_4 also absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The CH_4 GWP also accounts for some indirect effects, such as the factthat CH_4 is a precursor to ozone, and ozone is itself a GHG (USEPA, 2022).

Nitrous Oxide (N_2O) has a GWP 273 times that of CO_2 for a 100-year timescale. N2O emitted today remains in the atmosphere for more than 100 years, on average (USEPA, 2022).

Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6) are sometimes called high-GWP gases because, for a given amount of mass, they trap substantially more heat than CO_2. (The GWPs for these gases can be in the thousands or tens of thousands.) (USEPA, 2022).

Unlike many other greenhouse gases, fluorinated gases have no significant natural sources and come almost entirely from human-related activities. They are emitted through their use assubstitutes for ozone-depleting substances (e.g., as refrigerants) and through a variety of industrial processes such as aluminium and semiconductor manufacturing. Many fluorinated gases have very high global warming potentials (GWPs) relative to other greenhouse gases, so small atmospheric concentrations can have disproportionately large effects on global temperatures. They can also have long atmospheric lifetimes—in some cases, lasting thousands of years. Like other long-lived greenhouse gases, most fluorinated gases are well-mixed in the atmosphere, spreading around the world after they are emitted. Many fluorinated gases are removed from the atmosphere only when they are destroyed by sunlight in the far upper atmosphere. In general, fluorinated gases are the most potent and longest lasting type of greenhouse gases emitted by human activities (EPA, 2005).

There are four main categories of fluorinated gases—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6), and nitrogen trifluoride (NF3) (EPA, 2005).

2.17.7 Substitution for Ozone-Depleting Substances.

Hydrofluorocarbons are used as refrigerants, aerosol propellants, foam blowing agents, solvents, and fire retardants. The major emissions source of these compounds is their use as refrigerants—for example, in air conditioning systems in both vehicles and buildings. These chemicals were developed as a replacement for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) because they do not deplete the stratospheric ozone layer. Chlorofluorocarbons and HCFCs are also greenhouse gases; however, their contribution is not included here because they are being phased out under an international agreement, called the Montreal Protocol. HFCs are potent greenhouse gases with high GWPs, and they are released into the atmosphere during manufacturing processes and through leaks, servicing, and disposal of equipment in which they are used. Newly developed hydrofluoroolefins (HFOs) are a subset of HFCs and are characterized by short atmospheric lifetimes and lower GWPs. HFOs are currently being introduced as refrigerants, aerosol propellants and foam blowing agents. The American Innovation and Manufacturing (AIM) Act of 2020 directs EPA to address HFCs by providing new authorities in three main areas: to phase down the production and consumption of listed HFCs in the United States by 85% over the next 15 years, manage these HFCs and theirsubstitutes, and facilitate the transition to next-generation technologies that do not rely on HFCs.

Industry. Perfluorocarbons are produced as a by-product of aluminium production and are used inthe manufacturing of semiconductors. PFCs generally have long atmospheric lifetimes andGWPs near 10,000. Sulphur hexafluoride is used in magnesium processing and semiconductor manufacturing, as well as a tracer gas for leak detection. Nitrogen trifluoride is used in semiconductor manufacturing. HFC-23 is produced as a by-product of HCFC-22 production andis used in semiconductor manufacturing.

2.17.8 Transmission and Distribution of Electricity.

Sulphur hexafluoride is used as an insulating gas in electrical transmission equipment, including circuit breakers. The GWP of SF6 is 22,800, making it the most potent greenhouse gas that the Intergovernmental Panel on Climate Change has evaluated (IPCC, 2013).

2.17.9 Emissions and Trends

Overall, fluorinated gas emissions in the United States have increased by about 90% between 1990 and 2020. This increase has been driven by a 284% increase in emissions of hydrofluorocarbons (HFCs) since 1990, as they have been widely used as a substitute for ozone- depleting substances. Emissions of perfluorocarbons (PFCs) and sulphur hexafluoride (SF6) have actually declined during this time due to emission-reduction efforts in the aluminium production industry (PFCs) and the electrical transmission and distribution industry (SF6) (IPCC, 2013).

2.17.10 Reducing Fluorinated Gas Emissions

Because most fluorinated gases have a very long atmospheric lifetime, it will take many years to see a noticeable decline in current concentrations. However, there are a number of ways to reduce fluorinated gas emissions (IPCC, 2007).

2.17.11 Substitution of Ozone-Depleting Substances in Homes and Businesses

Refrigerants used by businesses and residences emit fluorinated gases. Emissions can be reducedby better handling of these gases and the use of substitutes with lower global warming potentials and other technological improvements. Visit EPA's Ozone Layer Protection site and HFC Phasedown site to learn more about reduction opportunities in this sector. (IPCC, 2007).

2.17.12 Industry

Industrial users of fluorinated gases can reduce emissions by adopting fluorinated gas recycling and destruction processes, optimizing production to minimize emissions, and replacing these gases with alternatives. EPA has experience with these gases in the following sectors:

2.17.13 Electricity Transmission and Distribution

Sulphur hexafluoride is an extremely potent greenhouse gas that is used for several purposes whentransmitting electricity through the power grid. EPA is working with industry to reduce emissions through the SF6 Emission Reduction Partnership for Electric Power Systems, which promotes leak detection and repair, use of recycling equipment, and consideration of alternative technologies that do not use SF6 (IPCC, 2007).

2.17.14 Transportation

Hydrofluorocarbons (HFCs) are released through the leakage of refrigerants used in vehicle air- conditioning systems. Leakage can be reduced through better system components and throughthe use of alternative refrigerants with lower global warming potentials than those presentlyused. EPA's light-duty and heavy-duty vehicle standards provided incentives for manufacturers to produce vehicles with lower HFC emissions (IPCC, 2013). A million metric tons is equal to about 2.2 billion pounds, or 1 trillion grams. For comparison, a small car is likely to weigh alittle more than 1 metric ton. Thus, a million metric tons is roughly the same mass as 1 million small cars. GHG emissions are often measured in carbon dioxide (CO_2) equivalent. To convert the emissions of a gas into equivalent CO_2, its emissions are multiplied by the global warming potential (GWP) of the gas. The GWP takes into account the fact that many gases are more effective at warming Earth than CO_2, per unit mass (Saunois *et al.*, 2020).

CHAPTER THREE

3.0 Aims of the Thesis

The main objective of this study is to produce biogas as a result of the decomposition processes of household waste in Nigeria.

To achieve this, the following specific research objectives would have to be met:

(1) Determine the best systems and methods used to dispose of household waste.

(2) Establish how household waste could be converted to biogas.

CHAPTER FOUR

4.0 METHODS

4.1 Description of the study area

The Federal Capital Territory is located just north of the confluence of the Niger River and Benue River. It is bordered by the states of Niger to the West and North, Kaduna to the northeast, Nasarawa to the east and south and Kogi to the southwest.

FCT is lying between latitude 8.25^0 and 9.20^0 north of the equator and longitude 6.45^0 and 7.39^0 east of Greenwich Meridian, Abuja is geographically located in the centre of the country.

The Federal Capital Territory has a landmass of approximately 7,315 km^2, and it is situated within the savannah region with moderate climatic conditions. And has 6 Area Councils.

The areas to be covered are the metropolis, satellite and villages from AMAC, Bwari and Kwali Area Councils respectively. The research was carried out in Soil Science and land management Department, Faculty of Agriculture, University of Abuja, Abuja, Nigeria (NGJ, 2013).

4.1.1 Household Waste Samples Collection

Household wastes were randomly collected at the three major settlements: metropolis in Abuja Municipal area council (AMAC), Satellite town in Bwari Area Council and villages in Kwali Area Council of the Federal Capital Territory, Abuja on the 12th of September 2022. In each settlement, Samples were randomly collected from households and mixed to get a true representation of household wastes.

Each sample gotten from a particular location after being thoroughly mixed, was measured seven kilograms (7kg) of waste for the three different locations.

After measuring out 7kg waste for each location, the wastes were carefully selected and arranged into the three (3) small scale biogas plant according to their sizes and rate of decay, representing three (3) locations in Abuja-FCT, Nigeria.

Cow dung was mixed with water and stirred continuously to get a perfect paste and it was poured into each of the small-scale biogas plant and this was basically for methanogenesis.

After this, the waste products were thoroughly mixed up with the cow dung and the biogas plant was closed and sealed up to prevent the penetration of oxygen.

Cow dung was collected from herdsmen settlement in Abuja and was stored a week before usage.

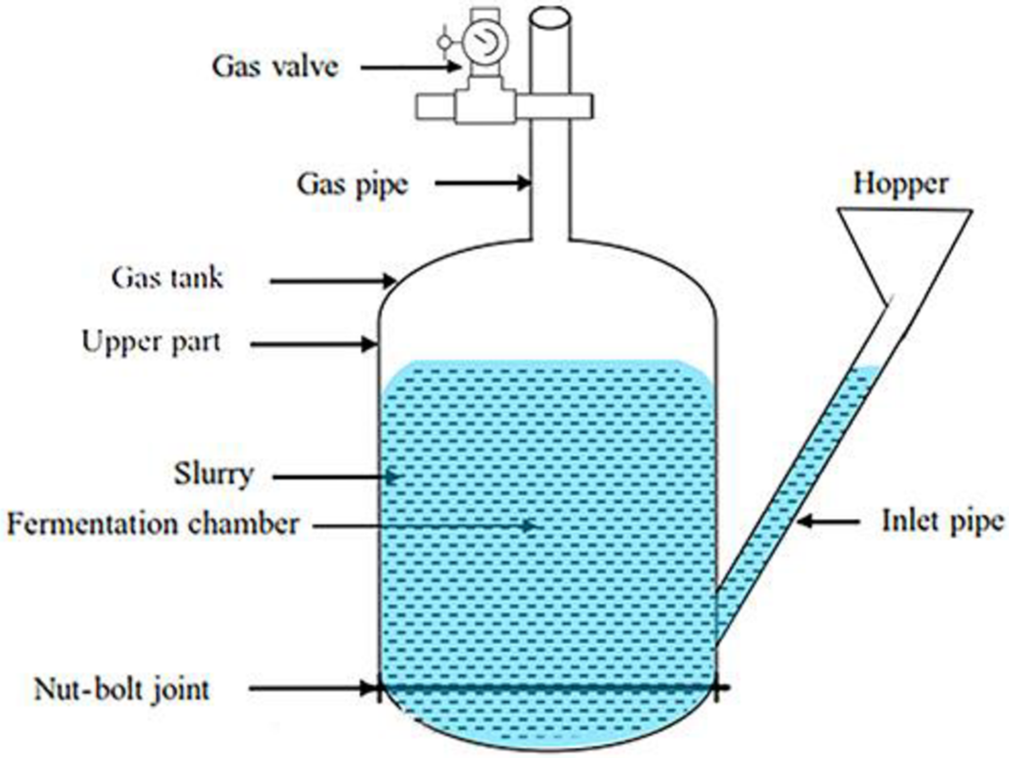

Figure 6. A biogas production system

4.2 Materials for Biogas Production

A biogas production system (figure 6) consists of the following features:

(a) **Substrate inlet (feedstock)**

This consists of a receptacle for the raw fresh organic waste and pipe of at least 10 cm diameter leading to the digester. The connection between the inlet pipe and the digester must be airtight.

(b) **Digester**

This is the reservoir of organic wastes in which the substrate is acted on by anaerobic microorganisms to produce biogas.

(c) **Gas Storage /Reservoir**

Depending on the proposed design, this may be simply an empty but enclosed space above the slurry in the digester, an inverted floating drum whose diameter is just slightly smaller than that of the cylindrical digester or an airtight polythene tube with an inlet –outlet outfit. vehicle tubes were used.

(d) **Gas Burner**

This may be a special lighting lamp or a modified burner for cooking.

(e) **Exhaust outlet**

This consists of a pipe of similar size to the inlet pipe connected to the digester at a slightly lower level than the inlet pipe to facilitate outflow of exhausted slurry.

All the materials were locally sourced (GTZ, 2011).

4.2.1. Production processes

Biogas can be obtained from any organic material after anaerobic fermentation by three main phases. The fermentation of organic wastes under anaerobic conditions to produce biogas occurs in the following three stages:

1. **First Stage**

Complex organic compounds are attacked by hydrolytic and fermentative bacteria, which secrete enzymes and ferment hydrolysed compounds into acetate and hydrogen. A small amount of the carbon converted will end up as volatile fatty acids, primarily propionic and butyric acids.

2. **Second Stage**

The hydrogen- producing acetogenic bacteria continue decomposing by converting the volatile fatty acids into acetate and hydrogen producing acetogenic bacteria.

3. **Third Stage**

Methane –producing bacteria convert the hydrogen and acetate into methane. There is a certain amount of specialization in that different bacteria act on different substrates. For these bacteria to work properly and achieve the desired end products, the following conditions must be well balanced.

(i)The dilution of the substrate i.e., amount of water to dilute the waste.

(ii) The optimum temperature which should be 35^0C.

(iii) Type of substrate (due to their suitable carbon to Nitrogen (C: N) ratio and total solid content cattle, pig and poultry manures are recommended).

(iv) Rate of feeding the digester (overfeeding can lead to accumulation of volatile fatty acids) (Ludwig *et al.*, 1991, Ludwig *et al.*, 1998).

4.3.0 Chemical determination of agricultural wastes:

The household wastes were air dried and chemical properties were determined based upon the total weight of selected materials used (FAO, 2008).

4.3.1. Determination of pH of Household waste.

Household wastes were weighed accurately and placed into each beaker and 100 mL of distilled water was added into each beaker (the ratio of sample to water was 1:4). It was shaken and heated for 30 minutes. It was cooled and filtered. The filtered was determined by digital pH meter.

4.3.2. Determination of total nitrogen by using Kjeldahl method:

0.5 g of each sample was put into 600 mL digestion tube and 1 g of catalyst was added. It was heated gently unit frothing ceases. The flask was removed from the heater and cool, distilled water was added and transfer to the suitable volumetric flask. Accurately 20-25 mL of 2% Boric Acid was placed in the receiving conical flask. 2-3 drops of methyl red indicator was added. Water was added enough to cover the end of the condenser outlet tube. 5 mL of aliquot pipette into the distillation tube and 5 mL of 40% NaOH was added, and the ammonia was distilled for about 4 minutes. The receiving flask was removed and rinsed the outlet tube into the receiving flask with a small amount of distilled water. Excess acid was titrated with 0.02 NH_2SO_4. Determine the blank a reagent in the same manner.

4.3.3 Determination of total phosphorus by using Molybivanado phosphoric acid method:

Pipette 5-25 mL of aliquot depending on P content in a 50 mL volumetric flask and add 5 mL of Barton's Reagent and dilute to 50 mL with distilled water. After 1 hour, measure with spectrophotometer at 420 nm.

4.3.4 Determination of potassium, calcium and magnesium by using atomic absorption spectroscopic method:

Potassium, calcium and magnesium content of household wastes were determined by Atomic Absorption Spectroscopic Method (AAS).

4.3.5. Determination of organic matter:

Loss of weight on ignition can be used as a direct measure of the Organic Matter (OM). The sample is ashed at 500-600°C by placing a suitable weight (0.5-1.0 g) of the sample in a silica crucible and heating it in a muffle furnace for 4-6 hours.

4.4 Data collection

Due to some issues, the expected daily production of gas will not be evaluated. However, from the incubation time, cooking time and the peak of production to achieve the optimal requirement.

The following data were collected; day, seconds of cooking, correspondent litres produced (biogas production rate) and the cumulated litres (biogas yield) were subjected to analysis of variance (ANOVA).

CHAPTER FIVE

5.0 RESULTS AND DISCUSSION

Table 5: Average value of chemical parameters of household waste before and after anaerobic digestion

Parameters	Before Anaerobic digestion	After Anaerobic digestion	P Value
PH	7.187±0.87260a	7.4525±0.12499a	0.132
Organic Matter	59.60±0.0165a	58.45±0.17078b	0.01
Carbon	30.3765±0.89846b	34.3775±0.08499a	0.004
Nitrogen	1.2465±0.09040a	1.45±0.12247a	0.230
C:N Ratio	19.32±0.090a	19.58±0.1247a	0.139
Phosphorus	0.4950±0.0768a	0.6950±0.0850a	0.131
Potassium	51.00±0.8165a	52.66±0.8498a	0.207

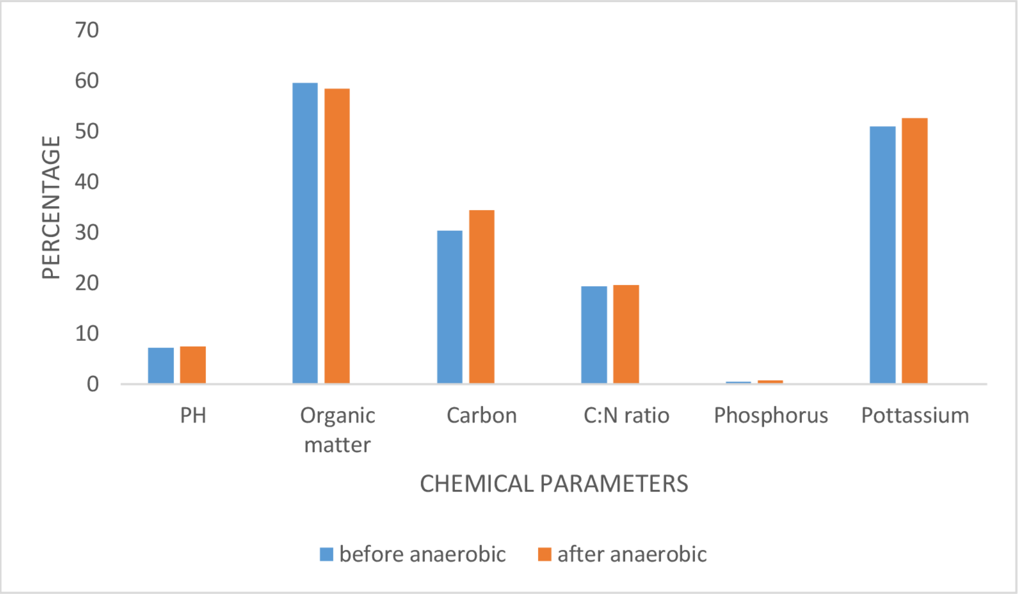

Figure 7: Average value of chemical parameters of household waste before and after anaerobic digestion.

5.1. Chemical Composition Changes during Anaerobic Digestion

5.1.1. pH Variation

The pH values of household waste before and after anaerobic digestion were assessed to understand the impact of the process. The pH slightly increased post-digestion (7.4525±0.12499a) compared to the initial pH (7.187±0.87260a), although this increase was not statistically significant (P=0.132). This result aligns with the findings of Gregor et. al (2022) who observed that increased pH-values of 6.6 from 5.5 during the anaerobic digestuon of food waste.

The final pH value shows a moderate alkaline change due to decomposition, which is advantageous for agriculture as many crops prefer slightly acidic to neutral pH soils. Thus, the bio-slurry resulting from anaerobic digestion has the potential to be used in soil pH regulation.

Previous research has also highlighted the positive impact of bio-slurry (BS) application on soil properties. Kinaghi (2016) demonstrated that the application of bio-slurry reduced soil acidity and contributed to the amelioration of agricultural soils, as evidenced in a study conducted in the Njombe Region of Tanzania. Additionally, the Food and Agricultural Organization (FAO) remphasized the soil amelioration potential of bio-slurry, noting its capacity to neutralize acidic conditions and enhance overall soil quality (FAO 2013).

5.1.2. Organic Matter and Carbon

Organic matter and carbon content significantly decreased after anaerobic digestion (P=0.01 and P=0.004, respectively). The C:N ratio remained almost the same before and after anaerobic digestion. The results shows that anaerobic digestion of household waste can lead to changes in the chemical composition of the waste, which could have implications for its use as a soil amendment. The decrease in organic matter from 59.60±0.0165a to 58.45±0.17078b shows efficient digestion of feeding materials. This C:N ratio was in line with that which was reported by Metcalf (2004) in the study of Thai canteens, stating a C:N ration of (20.52–30.88). This indicating the suitability for using food wastes as the co-digestion substrate for biogas production under anaerobic conditions.

The organic matter content before anaerobic digestion measured 59.60, decreasing to 58.45 after digestion. This reduction signifies effective decomposition during anaerobic digestion, transforming complex organic compounds into simpler forms. The process enhances the bioavailability of nutrients for plants and suggests a more stabilized and matured bio-slurry.

The initial carbon content was 30.3765, increasing to 34.3775 after anaerobic digestion. The rise in carbon content indicates the conversion of organic compounds into carbon-rich components during the digestion process. This carbon-rich bio-slurry can act as a valuable source of organic carbon, and has the potential to increase carbon sequestration through the supply of organic matter to the soil (Smith. et al, 2014). This in turn contributes to soil improvement, particularly in terms of structure and water retention.

5.1.3. Nitrogen, Phosphorus, and Potassium

The initial nitrogen content was 1.2465, which increased to 1.45 after anaerobic digestion. The significant increase in nitrogen content post-anaerobic digestion, shows that that the resulting bio-slurry could be used as a nitrogen-rich fertilizer, potentially enhancing both crop yield and overall soil fertility.

The initial phosphorus content was 0.4950, increasing to 0.6950 after anaerobic digestion. The rise in phosphorus content indicates its release during anaerobic digestion. As phosphorus is an essential nutrient for plant growth, the resulting bio-slurry could act as a phosphorus-enriched fertilizer, which would improve soil fertility.

The initial potassium content was 51.00, increasing to 52.66 after anaerobic digestion. The increase in potassium content is important for various physiological processes in plants. The bio-slurry, with increased potassium levels, could potentially enhance crop resilience and overall plant health.

The degradation of household waste through anaerobic digestion shows the bio-slurry's potential as a nutrient-rich fertilizer. The observed increases in nitrogen, phosphorus, and potassium content after anaerobic digestion signify a well-balanced and enriched composition. This suggests that the bio-slurry can play a crucial role in enhancing nutrient availability for plant growth, providing the essential elements necessary for optimal crop development.

Furthermore, the organic matter and carbon-rich characteristics of the bio-slurry have significant implications for soil structure improvement. The decomposition of organic compounds during anaerobic digestion contributes to the formation of stable organic matter, which contributes to better soil structure. This, in turn, facilitates improved water retention and supports microbial activity, creating a favourable environment for plant root development and nutrient uptake.

The observed slightly alkaline shift in pH, facilitated by the application of bio-slurry, can contribute to soil pH regulation.

Table 6. Elaborated values of gas produced and cumulated biogas yield

Location	**Biogas (g)**
Metropolis	22.0 (29.3ml)
Satellite	24.1 (32.1ml)
Outskirt (Village)	24.0 (32)
Grand mean	23.3 (31.1ml)
LSD	18.73
p-value	0.961^{NS}
SEM	5.74
Cooking time (seconds)	
0	0.0
90	20.0g
180	23.3g
270	30.0g
360	43.3g
Grand mean	23.3
LSD	24.19
PValue	0.033
SEM	7.42
Cumulative Biogas	
0	0.00
90	63.33g
180	73.33g
270	93.33g
360	133.33g
Grand mean	72.67
LSD	4.861
PValue	<0.001
SEM	1.491

Note: Means with different letters in a column are statistically significant at probability level of 5 %; LSD = Least Significant difference; P Value = Probability value at 5 % level of Significance; SEM = Standard Error of Mean; NS = Not Significant.

Table 6 represents the elaborated values of gas produced and cumulated biogas yield. The table shows the biogas production in grams (g) from three locations in Abuja: Metropolis, Satellite, and Outskirt (village), and the grand mean of biogas produced is 23.3g. The LSD (Least Significant Difference) for the grand mean is 18.73, and the P- value is 0.961NS, indicating no significant difference in biogas production among the three locations. Satellite produced the highest biogas, followed by outskirt and metropolis, respectively.

The observed variations in gas production across different locations in the study can be due to a multitude of factors that influence the anaerobic digestion process of household waste. These variations are attributed to the effects of waste composition, temperature variations, and microbial activity, all of which are connected to the geographical and environmental characteristics of each specific location.

Waste Composition

The composition of household waste can significantly differ from one location to another, influenced by various socio-economic and cultural factors. Different areas may generate waste with varying organic content, moisture levels, and overall nutritional value for microbial digestion. For instance, Han *et al.* (2019), while researching on characteristics and management modes of domestic waste in China, discovered that Waste from rural areas typically consists of a substantial amount of organic matter, including food scraps, vegetables, fruits, leaves, while having minimal recyclable materials. In the contrast, urban waste tends to have a higher proportion of non-biodegradable materials such as plastics, metals, and synthetic fibers due to increased consumption patterns and industrial activities (Okori *et al.* 2024). Additionally, urban waste often includes a significant amount of packaging materials from commercial products, contributing to its overall composition. Moreover, cultural practices and lifestyle choices can also influence waste composition (Nguyen et al. 2020), with certain communities exhibiting preferences for specific types of products or packaging materials, thereby impacting the waste stream. Understanding the composition of waste in different contexts is important for implementing effective waste management strategies tailored to the specific needs and characteristics of each region.

Temperature Variations

Temperature plays an important role in the efficiency of anaerobic digestion processes. Geographical differences lead to differences in climate and ambient temperature. Warmer temperatures generally speed up microbial activity, creating favorable conditions for anaerobic microorganisms regulating biogas production (Ruan et al. 2023). On the other hand, Microbial activity may be slower in colder environmental conditions when they are wet or cold, affecting the overall biogas production. Thus, changes in temperature in the studied areas lead to differences in the observed biogas production.

Microbial Activity

Microbial communities responsible for anaerobic digestion are highly sensitive to environmental conditions. The microbial composition in each location's varies, influencing the efficiency of the biogas production process. The presence of diverse microbial species and their adaptation to local conditions impacts the breakdown of organic matter into biogas components (Hashemi *et al.* 2021). Factors such as the types of bacteria present, their metabolic activities, and synergistic interactions within the microorganisms all contribute to variations in biogas production among locations.

Geographical and Environmental Factors

Geographical and environmental factors, including altitude, soil characteristics, and overall climate, have significant effect on waste decomposition and microbial activity. These factors create a unique ecosystem in each location, influencing the waste-to-biogas conversion process. For example, areas with higher altitudes experience lower atmospheric pressure, potentially affecting gas production rates. Additionally, soil composition impacts the availability of essential nutrients for microbial growth, further contributing to variations in gas production.

Progressive Increase in Biogas Production with Cooking Time

The table also presents the cooking time in seconds and the corresponding biogas production. The grand mean of biogas production is 23.3g, and the LSD for the grand mean is 24.19. The P-value is 0.0033, indicating a significant difference in biogas production among different cooking times. The biogas production increased with increasing cooking time until it reached the highest value of 43.3g at 360 seconds.

As the cooking time increasedfrom 0 to 360 seconds, there was a discernible and progressive increase in biogas production. This finding suggests that the duration of the anaerobic digestion process directly influences the quantity of biogas generated. The positive correlation between cooking time and biogas production is in line with the fundamental principles of anaerobic digestion, where prolonged exposure allows for the enhanced breakdown of organic compounds, leading to increased gas production.

Optimal Point at 180 Seconds

The study identified an optimal point for biogas yield at 180 seconds of cooking time, as indicated by the grand mean of 23.3g. This finding suggests that, within the assessed time range, 180 seconds is a key juncture where the efficiency of biogas production reaches its peak. Beyond this point, there was a drop in biogas production at 270 and 360 seconds, implying that extending the cooking time beyond the optimal point may not yield a proportional increase in gas production.

Significant Difference Indicated by LSD and P-Value (P=0.033)

The LSD (Least Significant Difference) and the associated P-value of 0.033 shows a significant difference in biogas production based on cooking time. This statistical significance emphasizes the reliability and validity of the observed trends. The P-value, in particular, suggests that the likelihood of the observed differences occurring by random chance alone is relatively low, reinforcing the robustness of the findings.

Implications for Biogas Production Optimization

Understanding the impact of cooking time on biogas production has practical implications for optimizing the efficiency of household waste-based biogas generation systems. The identification of the optimal point at 180 seconds gives a valuable parameter for system control and management. Adjusting cooking times within this range could be a strategy to maximize gas yield while avoiding unnecessary energy input and resources.

The findings contribute to the ongoing research on sustainable energy practices, particularly in the context of household waste utilization for biogas production. Efficient utilization of cooking time can lead to improved energy recovery from organic waste, which is in line with sustainable waste management practices and promoting the use of biogas as a renewable energy source.

Furthermore, the table shows the cumulative biogas produced at different time intervals. The grand mean of cumulative biogas production is 72.67, and the LSD for the grand mean is 4.861. The P-value is <0.001, whiuch indictaes a significant difference in cumulative biogas production at different time intervals. The cumulative biogas production increased with increasing time until it reached the highest value of 133.33g at 360 seconds.

Steady Increase in Cumulative Biogas Yield

The observed grand mean cumulative biogas yield of 72.67g signifies a consistent and incremental rise in gas production over the evaluated time periods. This steady increase is indicative of the continuous and effective conversion of organic waste into biogas, showcasing the resilience and reliability of the anaerobic digestion process. The trend suggests that, as the digestion process progresses, more organic matter is transformed into biogas components.

The significance of cumulative biogas yield over time implies that the efficiency of the biogas generation process is influenced by the cumulative impact of various factors, such as microbial activity, waste composition, and operational conditions, throughout the entire digestion period. This finding is instrumental for optimizing biogas production systems, as it suggests that interventions or adjustments made at any point in the process can have a cumulative effect on overall gas yield.

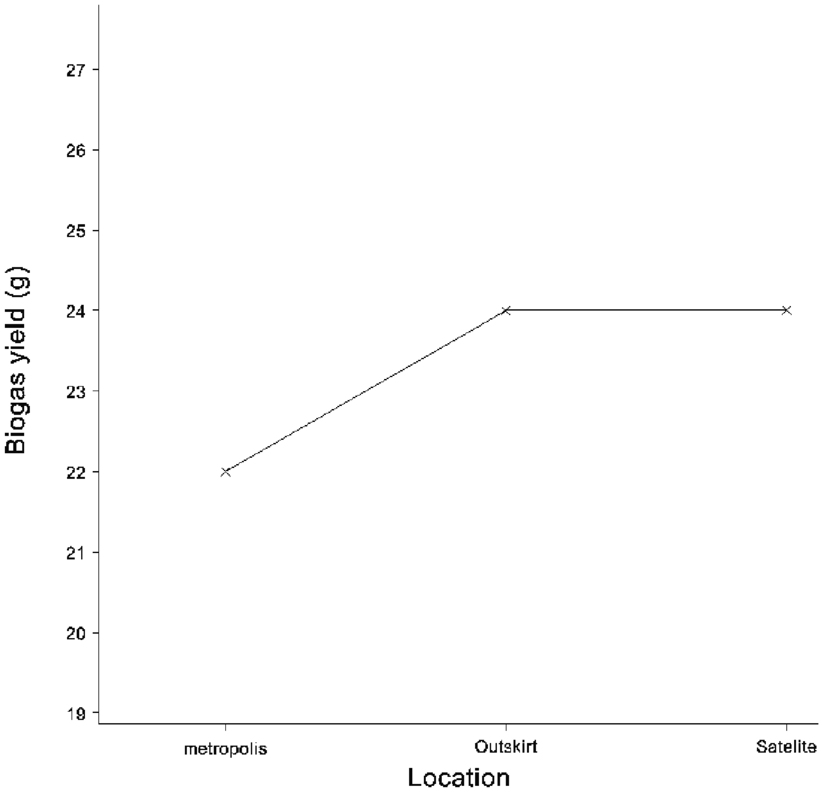

Figure 8. Elaborated values of biogas produced from household waste of different locations.

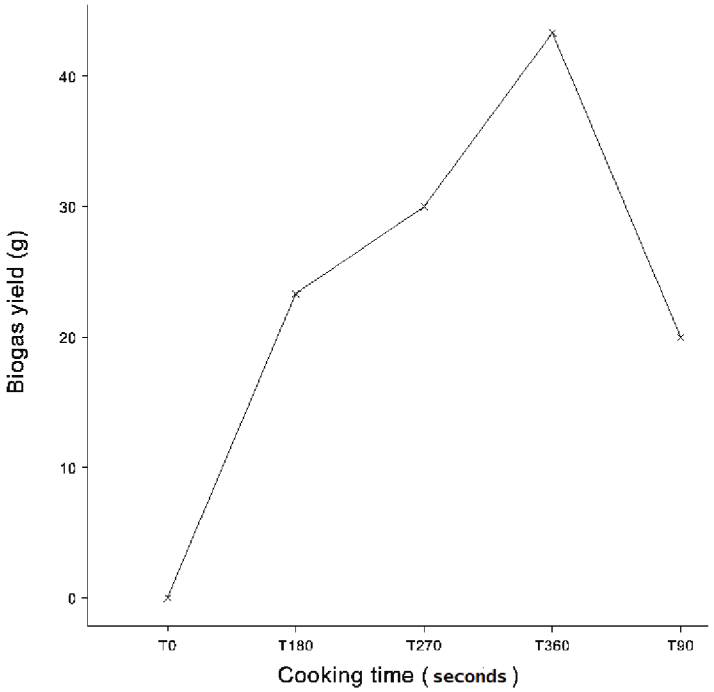

Figure 9. Biogas produced from household waste in seconds

The anaerobic digestion process is an appropriate procedure for the treatment of municipal solid waste for further generations of bioenergy. It is an adequate method for treating food waste.

From Table 6 above, the value of biogas produced from three locations in Abuja; metropolis, satellite and outskirt were not significantly different at 5% level of probability. However, waste obtained from satellite location produced the highest value of biogas with a value of 24.1 g, followed by the outskirt with a value of 24.0g and metropolis (22.0g) respectively (figure 9). It was established that there was enough waste (100kg per day) for production of sufficient biogas of about 24m^{3}per day to substitute the use of wood fuel and liquid petroleum gas (Ogur and Mbatia, 2013) The volume of biogas generated could be as the result of the composition of the wastes from different locations.

Biogas volume based on time of cooking, showed a significant level at 5% level of probability in second at three different locations; metropolis, satellite and the outskirt to days of production. However, there was no significant difference among the locations respectively.

Biogas production started 21 days after the setup of anaerobic digesters with 180 second of time of cooking period with a production of 23.3g, 23days of 360 seconds of cooking period with a production of biogas 43.3g, 25days of 270 seconds of cooking period with a production of 30.0g and 30 days of 90 seconds of cooking period with the production of 20.0g of biogas. However, there were all significantly different at 5% level of probability to 0-21 days of zero second of cooking period with zero production of biogas.

There was a highly significant difference at 5% level of probability in cumulative biogas production base on time of production and days of production. Cumulative biogas yield at 21 days after the setup of anaerobic digesters with 180 second of time of cooking period with a production of 73.33g, 23days of 360 seconds of cooking period with a production of biogas 133.33g, 25days of 270 seconds of cooking period with a production of 93.33g and 30 days of 90 seconds of cooking period with the production of 63.33g of biogas. However, there were all significantly different at 5% level of probability.

A few studies have been conducted under psychrophilic conditions due to the slow degradation speed and the long retention time; despite the benefits of the two-stage psychrophilic digester (Rusín *et al.*, 2020), it requires more space and is more costly. On the other hand, the co-digestion of two substrates or more has been reported as an efficient method to maintain pH value (Gao, *et al.*, 2021), to reduce VFA accumulation (Cheng *et al.*, 2021), and ammonia inhibition (Begum *et al.*, 2021), and to increase the AD performance in high TS which ultimately improves methane production. It is difficult to determine an appropriate ratio for diverse feedstock since the best mix of feedstock is influenced by a variety of characteristics such as feedstock type, composition, trace element concentration, and biodegradability, among others (Karki, *et al.*, 2021). Even if a common ratio such as C/N has been reported to influence energy recovery (Cheng *et al.*, 2021), we cannot ignore the effect of moisture and other environmental factors.

In addition, the pre-treatment methods have a good ability to maintain pH value (Gnaoui *et al.* 2020), enhance methane generation (Yuan *et al.*, 2021).

The average methane content was calculated to be 48.89% and according to Karki et al, (2015), biogas consists of 50-70% of methane and 30-40% of carbon dioxide. The obtained percentage of methane was near the range. Lesser volume of methane may be because of the presence of carbohydrates like potato peels, cooked rice and food leftover in the feeding materials.

AD is more susceptible to by-product inhibition, such as VFA and ammonia, which have a negative impact on the process and can cause system failure. However, the monitoring and the adjustment of the parameters, such as temperature, pH, OLR, TS (%), and C/N ratio can be good for both process stability and biogas production. Furthermore, there are other significant parameters that are not included in this research, such as volatile solid removal VSR (%), TVFA/ alkalinity ratio, soluble COD percentages substrate/ inoculum ratio, etc (Benyahya et al, 2022).

Hence, Sapkota et al, (2012) obtained 32.121/ kg of biogas from kitchen waste. According to (Zupancic and Grilc, 2012), municipal organic waste contains 0.5-0.8m^3/kg of Volatile Solid (VS). The obtained volume of biogas in this study was found to be less than both studies. The low production of biogas maybe as a result of the improper digestion of the canteen’s waste, overfeeding of the waste in the digester and the shade of the tree located behind the biogas plant preventing the direct sun rays to the bio-digester.

CHAPTER SIX

6.0 CONCLUSION

In conclusion, this study has shown the significant potential of household waste as a viable feedstock for biogas production, establishing its role in both waste management and renewable energy generation. The anaerobic digestion process proved effective not only in increasing the nutrient content of waste, but also in producing biogas as a sustainable energy source. The findings show the importance of waste quality, with the Abuja satellite site producing the highest volume of biogas, highlighting the critical role of waste composition in the efficiency of biogas production systems.

The nutrient rich slurry generated after anaerobic digestion is an opportunity to improve soil fertility, thus contributing to improved agricultural production. However, further research is needed to dtermine the optimal application rates for different crops and soil types based on the application of the slurry as fertiliser .

Additionally, the study highlights the potential of household-scale biogas technology as a decentralised and sustainable energy source, particularly in rural areas where access to traditional energy sources can be limited.

The observed declining trend in biogas production over time reveals that there is need for optimisation in both the design and operation of biogas digesters to improve efficiency and minimise losses. This insight shows the importance of ongoing research and development efforts to refine biogas production technologies and practices.

6.1 RECOMMENDATIONS

Based on the conclusions drawn from this study. There are several recommendations to further develop the use of household waste for the production of biogas.

The declining trend in biogas production over time suggests the need for a meticulous review and optimisation of the biogas digester design. Enhancements in design parameters, such as size, shape, and material, will contribute to sustainable and efficient biogas generation.

Further research should focus on determining the optimal application rates of the slurry for different crops and soil types. The conduct of systematic studies will provide specific guidelines for farmers, ensuring the judicious use of the nutrient rich slurry to enhance soil fertility without causing adverse effects.

Due to the potential of household-scale biogas technology in rural areas, efforts must be made to disseminate the benefits and significance of this technology to them. Educational programmes and community outreach initiatives can play a crucial role in polarizing knowledge and enabling the adoption of decentralised biogas systems.

Also, policy makers should consider integrating household waste-based biogas production into waste management policies. Incentives and regulations that promote the adoption of biogas technology will contribute to the dual benefits of effective waste management and renewable energy generation.

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APPENDICES

Appendix 1: Anaerobic digestion set up

Appendix 2: Filling Biodigester

Appendix 3: Final Set Up

Appendix 4: Final Set Up

Appendix 5: Fabricated anaerobic digesters