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Decomposition Processes of Household Waste via Small Scale Biogas Technology: A Case Study of Nigeria

MASTER'S THESIS

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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

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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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List of the abbreviations used in the thesis

AD - Anaerobic Digestion

ASBR - Anaerobic Sequencing Batch Reactor

BOD - Biochemical Oxygen Demand

C/N - Carbon-nitrogen ratio

COD - Chemical Oxygen Demand

CSTR - Continuous-Flow Stirred Tank Reactor

DM - Dry Matter

FCT - Federal Capital Territory

HRT - Hydraulic Retention Time

LPG - Liquid petroleum gas

OLR - Organic loading rate

SDGs - Sustainable Development Goals

UASB - Up flow Anaerobic Sludge Blanket (UASB)

VFA - Volatile Fatty Acids

VS - Volatile Solid

VSR - Volatile solid removal

1. INTRODUCTION

Household waste management is a critical environmental challenge, especially in developing countries like Nigeria (Nwosu and Chukwueloka, 2020). With rapid urbanisation and population growth, the volume of waste generated is increasing, leading to significant environmental pollution and public health concerns (Nwosu and Chukwueloka, 2020). Traditional waste disposal methods, such as landfilling and open burning, contribute to greenhouse gas emissions and other environmental issues (Siddiqua et al., 2022). Small-scale biogas technology presents a sustainable alternative for managing household waste while producing renewable energy (Lohani et al., 2021).

Discussions about renewable energy has continued to gain global attention as a result of the need for sustainability to save our environment from the consequent effect of global warming which we are currently experiencing (Gunnarsdóttir et al., 2021). According to (), our environment is changing and the changes we are seeing in our environment are an effect of the activities such as deforestation, agriculture, improper management of waste among other activities which are consequently effecting the environmental wellbeing (Bish et al., 2020). Additionally, Xu et al. (2018), noted that the global population is increasing at an annual rate of about 2% with an exponential growth to around nine billion by the year 2050 (Srisowmeya *et al.*, 2020). This increase in population is also expected to lead to increased economic and industrial activity in all sectors and thus an increase in waste generated both organic and inorganic waste (Ravindran et al., 2021). These wastes are classified into industrial waste, municipal solid waste and animal waste (manure) (Peng et al., 2023).

However municipal solid waste seems to be a major challenge for the environment due to number factors which include weak environmental laws and lack of proper logistics to effectively manage these wastes (Batista et al., 2021). Unlike the industrial waste, which are strictly monitored by government agencies, municipal solid waste management lack strict regulation and they form the largest proportion of solid waste generated by households in Nigeria (Kassah, 2020). However, digging further into the composition of municipal solid waste shows that these wastes is made up of both organic and inorganic waste (Batista et al., 2021). The inorganic component of the waste is made up of plastics, metal, paper, nylon and other waste which are not easily decomposable while the organic waste are mainly made up of household food waste (Batista et al., 2021). These households food waste decompose rapidly and are quite difficult to manage due to the stench released when these waste are being decomposed (Batista et al., 2021).

Studies have shown that the rate of generation of the organic waste will keep growing with increase in population and these creates an even much more interesting challenge awaiting significant solutions (Bhatia et al., 2020). Figures shows that between 1.3 to 1.6 billion tons of food end up in the waste dump every year (Gallipoli *et al.*, 2020). On the average, these waste has the potential of generating about 290 billion m^3 methane and about 4.4 to 5.4 gigatonnes of CO_2 equivalent (Gallipoli *et al.*, 2020). This volume of greenhouse gases is quite much and poses a significant impact in the environment and even on the wellbeing of the populace (Gallipoli *et al.*, 2020). This is coupled with the fact that these wastes are not effectively managed with a whole lot of it ending up in landfills, open dumps, burning site and other unconventional waste disposal sites, which are used (Caicedo-Concha *et al.*, 2019).

In addition to these, the continuous growth of urban cities have made the use of open dumpsites a challenge (Aluko et al., 2020). This is because as the cities grow development of housing and infrastructures have expanded towards those areas and these are not healthy for the populace (Aluko et al., 2020). For instance in Lagos state, Nigeria the dumpsite at Ojota was created to when the city was not developed but the fast growth of Lagos state meant that the dumpsite is located within residential neighbourhood with the stench of decaying waste being smelt from places that are far away from the dumpsite (Oyebode et al., 2023). This case is not only peculiar to Lagos state but to many urban cities in Nigeria where dumpsites coexists side by side with urban settlements (Oyebode et al., 2023). This situation is quite unsettling because of the fact that this situation could have negative effect on the neighbourhood in terms of contamination of underground water, which is a major source of water. The smell released from these dumpsites could have negative effect on the health of the people in those vicinities due to the dangerous chemicals released in the decomposition process (Wang et al., 2021). According to Kumar and Samadder (2020), urban areas keep expanding and the demand for lands in proximity to urban areas puts people at risk of the environmental dangers associated with the management of the wastes at dumpsites.

Some of the approach that has been proposed for the management of food waste include the use of composting which helps in enhancing the health of the soil (Kim et al., 2020). The challenge with the use of this process is that with the volume of waste generated the approach may not be sustainable on the long run and might still result in lot of waste not being effectively utilised and thus partially solving the problems (Peng et al., 2023).

However, the continuous increase in the energy needs and the need for an effective means of waste management provides an opportunity to introduce small-scale biogas technology to households in Nigeria (Okoro et al., 2020). Some of the benefits of the utilisation of waste in generating energy include the fact that it ensures that the organic waste is properly disposed and treated and through this reduce environmental pollution and health hazards (Okoro et al., 2020). The other benefit include the fact that it helps in the generation of renewable energy and through this reduce the reliance on firewood and fossil fuels and through this process reduce deforestation and reduce greenhouse gas emissions (Tolessa, 2024). From the economic angle, it has the potential of creating jobs and supporting food production with the production of organic fertilisers (Tolessa, 2024). In essence, proper treatment of food waste can help in providing clean energy, reduce volume of waste and help in protecting the environment.

The importance of energy among households for the purpose of domestic activities makes this approach viable for sustainable economic development. The achievement of energy security, which at the present is a challenge for the nation with increasing energy prices and the need for government to find cheaper alternatives for its citizenry, which is renewable and does not put pressure on the environment. Therefore, as the demand for fossil fuels continues to increase due to the need to power economies to deliver, the challenge it brings to the environment has made it ever increasing to focus more on the development of renewable energy sources. Thus, the need to promote small-scale biogas technology to enable households manage their energy needs while also contributing to effective waste management. As such Biogas seems to be a better approach for the future with oil wells drying and many activism going on about the environment. It is best understand how best to utilise biogas using household waste.

Biogas is a combination of gases produced by microorganisms through the use of organic waste which have been decomposed in an anaerobic environment with the aid of microorganisms (Giampietro, 2008). The gas has about 50 to 70 percent methane (CH_4), 30 to 40 percent carbon dioxide (CO_2) and minute levels of other gases. The gas is an odourless and colourless gas that burns with a clear blue flame similar to that of liquid petroleum (LPG) gas (Drapcho et al., 2008). Depending on the task and the availability of fuel in the area, gas can be used as a fuel substitute for firewood, dung, agricultural residues, petrol, diesel and electricity (James and James, 2012).

1.1. Justification

Household waste, particularly organic waste, contributes significantly to environmental pollution (Karic et al., 2022). Traditional waste disposal methods, such as landfilling and open burning, release methane (a potent greenhouse gas) and other pollutants into the atmosphere (Karic et al., 2022). These practices not only contribute to global warming but also cause local environmental degradation, including soil and water contamination (Oyebode et al., 2023). As such, implementing small-scale biogas technology can mitigate these environmental impacts by reducing greenhouse gas emissions and minimising pollution (Tolessa, 2024).

Furthermore, small-scale biogas systems are particularly suitable for Nigerian households due to their adaptability and scalability in terms of their low Initial Investment when compared to large-scale waste management and energy production facilities, small scale biogas systems require lower initial investments, making them accessible to low-income households (Ketuama et al., 2022). Additionally, these systems can be easily scaled up or down depending on the waste generation and energy needs of different households or communities (Ketuama et al., 2022).

In addition, the introduction of small-scale biogas technology aligns with the united nations sustainable development goals (SDGs) such as the goal seven which include the provision of affordable and clean energy (Dalei et al., 2021). Additionally goals 13 which is aimed at climate actions to reduce greenhouse gas emission (Kuramochi et al., 2020) and goal fifteen which is targeted at life on land by protecting protects terrestrial ecosystems and preventing degradation through sustainable waste management (Monaco, 2024). As such, these study contributes to the body of knowledge on meeting the SDG goals.

Due to population expansion, organic waste—especially household waste—now poses a serious global problem. Anaerobic digestion (AD) is a crucial procedure that significantly boosts the value of organic waste, especially food waste, by producing biogas, a renewable energy source, and rich-nutrient residue that may be used as biofertilizer. Because AD produces compost and biogas, it enables good recovery of domestic trash. Nonetheless, a number of important elements have an impact on how AD operates. My aim is to include a variety of important factors in this project that affect the AD process, such as temperature, pH, total solid content (TS(%)), organic loading rate (OLR), and carbon to nitrogen ratio (C / N).

Additionally, the study will emphasise the inhibition brought on by an excessive build-up of ammoniac and volatile fatty acids (VFA), demonstrating the benefits of co-digestion, pre-treatment strategies, and mixing techniques for preserving process stability and boosting biogas output. I will examine some of the most recent mathematical models that have been studied in the literature, including separate generic, coupled, non-structural, and kinetic first-order models. Lastly, the study will go over some issues, offer some potential fixes, and offer a look ahead. These materials should prove to be very helpful to researchers who are interested in large-scale household waste recovery for biogas generation.

2. LITERATURE REVIEW

2.1. Climate Change, Waste Management, and the Crucial Role of Biogas

Climate change measures the changes in weather events over a long period of time (Seneviratne et al., 2021). The issue of climate change has continued to be a major worry globally due to the fact that weather are changing rapidly and difficult to predict. Additionally, here has been a widespread report of disasters, which are related to the changes in climate such as flooding, desertification, wildfires, high intensity of heat among many others (AghaKouchak et al., 2020). However, it is of concern that the major factors that has led to the issue of climate change are mainly man made because of uncontrolled human activities like agriculture, industrial activities among many others, which have changed the outlook of the environment (Seneviratne et al., 2021).

Specifically, the burning of fossil fuels from industries, transportation, domestic activities releases greenhouse gases like carbon dioxide, trapping heat and causing global warming. In addition, landfills, a major component of waste management, contribute significantly to climate change through methane emissions as the waste decomposes (Kabir et al., 2023). According to Devadoss et al. (2021), 6,898,167 tonnes CO2-eq of GHG emissions was from solid waste disposal sites (SWDS) and this is of great concern because of the fact that waste generated through human activities has continued to increase over time. This implying that the contribution of this waste to climate change continues to increase. Essentiallyh, methane that is released from the disposal of decomposing organic waste is a potent greenhouse gas, with 25 times the heat-trapping capacity of carbon dioxide over a 100-year period (Azhar et al., 2024). As such, when organic waste decomposes anaerobically (without oxygen) in landfills, it generates methane that contributes to climate change.

Rapid urbanisation and population growth has led to an increase in waste generation, especially organic waste from food scraps (Ashokkumar et al., 2022). At the moment, many developing countries lack adequate waste collection and infrastructure, leading to open dumping and burning, further polluting the environment and the traditional waste management practices often used in these countries rely on landfills, which have limited capacity and pose environmental risks like leachate contamination and methane emissions (Chavan et al., 2022). According to Nwokolo et al (2020), the problems of climate change and waste management can be further mitigated using Biogas technology, which makes use of an anaerobic digestion process to breakdown organic waste into biogas, which is useful for household purposes. Thus reducing the level of organic wastes in landfills and combating the release of methane gas, which is one of the major causes of climate change. It also provides a clean and renewable source of energy for cooking, lighting, and potentially electricity generation, reducing reliance on fossil fuels and associated greenhouse gas emissions (Nwokolo et al., 2020).

As such, biogas can be an effective way of mitigating the effects of climate change through the production of biogas from organic waste, reducing the level of organic waste by utilising it appropriately and then contributing to the production of renewable energy sources (Czekala, 2022). It can also promote sustainable development by promoting energy security, improving sanitation, and supporting sustainable agricultural practices, particularly in rural areas (Czekala, 2022).

2.2. Overview of household waste management and its impact in Nigeria

Solid waste includes all wastes that are generated from both man and animal activities (Dehgani et al., 2021). Examples of wastes include household wastes, which are made up of leftover foods, papers, and polythene packages/bags among other types of waste (Olukanni et al., 2020). Household waste management is a critical aspect of environmental sustainability and public health (Abubakar et al., 2022). Effective waste management involves a series of activities and processes aimed at reducing the volume of waste generated, ensuring proper disposal, and promoting recycling and recovery of materials (Olukanni et al., 2020). Nigeria faces significant challenges in managing its household waste (Albert and Olutayo, 2021). Rapid urbanisation and population growth, and changing consumption patterns have led to an increase in waste generated particularly organic waste from food scraps (Sharma et al., 2020). However, the existing infrastructure and practices struggle to keep pace with this growing problem. The issue of household waste management in Nigeria is quite pressing because of issues like rapid urbanisation, population growth, and inadequate waste management infrastructure (Albert and Olutayo, 2021). Of recent, there has been an increase in the quantity of waste generated in the country and this is mainly caused by rapid urbanisation (Olukani et al., 2020). With more than half of the country's population living in the urban areas and an annual urban growth rate of about 2.53% as at 2020 (Abubakar, 2022). There is an increasing amount of waste being dealt with in these areas (Olukanni et al., 2020). Despite efforts to address the problem, significant challenges persist, affecting environmental sustainability and public health.

As such, this has become a major concern to both households in the urban and rural areas of the country. It has been found out that developing countries like Nigeria spend about 2 to 25% of their budget on household waste management (Jagun et al., 2023). However, the efficiency of the waste collection system is still questionable due to the level of garbage of waste decomposing in major areas in the cities like rivers, road medians, bushes and junctions among other areas (Jagun et al., 2023). This raises critical issues as to its effect on the wellbeing and health of the populace because of its after effect, causing pollution in water bodies, air and even leading to greater public health challenges like typhoid, cholera among others (Olukanni et al., 2022).

Specifically, solid waste management is one of the greatest challenges facing the state and the local governments in Nigeria and it is always a common site to behold when entering into major cities like Lagos, Ibadan, Abia among others (Nwosu and Chukwueloka et al., 2020). Over the years, there has been more awareness by states on solid waste management through the creation of agencies in charge of it who have the sole responsibility of assigning waste managers to residence and ensuring proper disposal of waste (Ezeudu et al., 2021). There has also been the rise of environmental protection agencies, sanitation officers and even in some cases; some states have special days for environmental sanitation programs (Ezeudu et al., 2021). However, this has not stemmed the tide of improper waste management has smells of burnt refuse and blocked drainage are still common scenario (Albert and Olutayo, 2021). These heaps of refuse contributes to the pollution of the environment and adds to the increases in diseases like diarrhoea, cholera, typhoid among other public health issues (Albert and Olutayo, 2021).

Nigeria has a population of more than 200 million people and this is expected to increase to around three hundred million by the year 2050 (Olowe, 2021). However, with the present state of household waste management in the country, it might spiral into a public emergency as the population grows as such the need to take concrete steps to stem the tide. To understand the magnitude of the situation clearly, more than 2 billion tons of waste is generated globally on an annual basis with around 32 million tons of solid waste generated from Nigeria annually, which is classed as one of the highest in Africa (Mama et al., 2021; Ezeudu et al., 2021). The waste generated among households is made up of, predominantly organic materials like food scraps, yard waste with also plastics, paper, metals, and glass making up the remaining composition (Adekunle et al., 2020). From the waste generated only about 20% to 30% of the waste is collected or recycled (Olukanni et al., 2020). This means that more than 70% to 80% of waste generated is left to other means of waste disposal and therefore there use cannot be accounted for. Specifically, urban areas, especially megacities like Lagos generate more waste that rural areas because of higher population density and the consumption pattern of people living in the state (Dawodu et al., 2022). According to Adekola et al. (2021), the rate of urban development has created a big issue for effective waste management with the strategies put in place not in tandem with the demands for waste management by the government at each level. This implying an inefficient waste management system.

At present, the management of solid waste in Nigeria is rife with many challenges, which include the collection process of waste, which is often inefficient and irregular, especially in informal settlements with many households lack access to regular waste collection services (Shittu et al., 2021). This has caused households to seek for alternatives means of waste disposal. These alternatives include dumping of wastes in rivers and streams (Dawodu et al., 2022). Dumping of waste by the roadside, bushes or unregulated dumpsites, burning of refuses in residential areas among other means of waste disposal (Olukanni et al., 2022). Adekunle et al (2020) further noted that urban households usually rely on indiscriminate practices like dumping of refuse in unauthorised places, burning, burying of solid waste within their vicinities among other strategies as a means of waste disposal. This means of disposal has been found to contribute to the degradation of the environment through the release of pungent smells and even dangerous gases when these refuses are being burnt.

It also causes health and environmental risks through leachate and methane emissions (Shittu et al., 2021). As such, these has led to increased need for more actions in the management of waste. This is because of the projected increase in development and economic activity, which is likely to drive things like urbanisation and increased consumption and then further exacerbating the waste management issue the country is currently facing (Olowe, 2021).

On regulation and policies, the Federal Environmental Protection Agency (FEPA) was established in 1981 to cater for these and with the establishment of this agency, many states in the country established their own waste management authorities for the purpose of management and regulation of waste (Tijani, 2021). However, these agencies have not been successful because of the lack of empowerment and sanctions for defaulting people (Tijani, 2021). Additionally, FEPA was replaced with the National Environmental Standards and Regulations Enforcement Agency (NESREA), by the Nigeria government with the aim of ensuring proper waste management, has not been able to do much despite their coverage in almost all the states of the federation (Tijani, 2021). In addition, laws of the country on waste management which is tagged the harmful waste (special criminal provision) act of 2004 which "prohibits carrying, deposition and dumping of harmful waste on any land, territorial water, and other related thereto" among other environmental laws lacks enforcement (Eberinwa, 2023). Even the law has been reviewed to include climate change considerations and actions needed to show Nigeria's commitment to the Climate Agenda 2060 (Eberinwa, 2023). However, these has been ineffective. This may be largely due to the ineffectiveness of government in providing alternative waste management system that can effectively cater for the disposal needs of the populace, due to the fact the enforcement of laws are weak, and lacks coordination between federal, state, and local governments (Tijani, 2021). It should be noted that the right policies are important for an effective waste management system. In the cases where policies are weak or the environmental laws lack implementation, the management of waste becomes a serious challenge (Eberinwa, 2023). Based on the circumstances reviewed so far most urban areas in Nigeria are viewed as dirty and unsanitary thereby raising the need for an urgent means of effective waste management (Olukanni et al., 2020).

Recycling has been recognised as one of the best methods for waste management in Nigeria and there has been efforts among some big states in Nigeria to recycle waste (Oh and Hettiarachi, 2020). However, this is still farfetched because a little percentage of waste generated are being recycled and if the collection system is not improved, recycling may still be a dream in the pipeline (Ezeudu et al., 2021). Additionally, recycling activities are primarily driven by the informal sector, where waste pickers collect and sell recyclable materials (Ogwueleka and Naveen, 2021). With formal recycling activities still underdeveloped. Although waste is seen as a burden but when effectively put to use it can be a wealth generator and can stimulate economic development (Ogwueleka and Naveen, 2021). However, the challenges of waste management in Nigeria stems from the fact that it lacks the required publicity with little awareness being created about it (Olukanni et al., 2020). It should be noted that the high organic content in waste generated by households presents opportunities for composting and biogas production (Ogwueleka and Naveen, 2021).

2.3. Importance of Waste Management using biogas

Waste is a serious issue for the environment and in sub-Saharan Africa and especially in Nigeria where waste management is challenging and poses a risk to the environment (Ayeleru et al., 2020). The use of biogas is a viable means of managing waste especially with the advent of small-scale biogas technology, which if used by households can meet their energy needs (Czekala, 2020). The benefits gotten from the use of household waste for biogas generation can be viewed from three dimensions of impact using the triple bottom theory framework, which explores impact from the environment perspective, economic perspective and the social perspective.

From the environmental benefit perspective, the generation of biogas from waste contributes to the reduction in greenhouse gas emission generated from the unconventional means of waste generation, which has been found by studies of Mahmudul et al. (2022), to be a significant cause of greenhouse gas release in developing countries like Nigeria, and serves as a renewable energy sources. The waste, which are dumped in landfills, produces methane, which is a greenhouse gas that is potent and has been identified as major greenhouse gas produced (Mahmud et al., 2022). However, the biogas technology benefits the environment by capturing these greenhouse gases and utilising it for other purposes thereby reducing the volume of release of this gas and other potent gases into the environment (Kapoor et al., 2020). In addition, the level of dependence on fossil fuels like firewood in rural sub Saharan Africa especially in Nigeria is high and thus the use of biogas can help in reducing this dependence by encouraging the use of a cleaner and cheaper energy source when compared to the conventional alternatives (Kapoor et al., 2020). The use of biogas can also help in protecting the forest and biodiversity since the dependence on the forest for energy source will be drastically reduced (Ali, 2021). Other benefit to the environment include the waste volume reduction, which is because of the anaerobic digestion and thus reducing the level of land and water pollution and the burden on landfills (Kapoor et al., 2020). Also, waste produced from the bio digester serve as a sustainable alternative to the use of chemical fertilisers which have been reported to be detrimental to the environment (Kapoor et al., 2020).

The Economic benefit of the use of waste for biogas stems from the fact that biogas falls under the renewable and sustainable energy sources (Kabeyi and Olanrewaju, 2022). Thus, the economic benefit comes from the fact that the use of renewable energy sources could offer a cheaper alternative to the conventional energy source in areas where the cost of energy is high (kabeyi and Olanrewaju, 2022). The introduction can also help in stimulating local economies by creating jobs and employment opportunities while enhancing economic growth (Czekala, 2022). This is especially valid in areas where there is limited or no energy access thereby helping the people in the locality to beef up their economic activities and improving their ability to generate income (kabeyi and Olanrewaju, 2022).

From the social perspective, the use of waste for biogas generation could help in controlling or stemming the tide of diseases related with improper waste disposal like typhoid, cholera and malaria (Zeldovich, 2021). This is because of the reduction in the vectors carrying the disease organism such as flies and rodents, and lowers the incidence of waste-related diseases (Zeldovich, 2021). Additionally, the use of household waste for biogas provides a cleaner energy alternative when compared to the other energy sources used by low-income earners or rural based households (Lohani et al., 2021). This can in itself help in reducing indoor air pollution and associated health risks, which are already a concern to public health specialist because of the increase in disease related with inhaling smoke from the cooking areas (Lohani et al., 2021). The use of the technology also improves community life due to access to energy that can help in empowering the households and making them more productive (Czekala, 2020).

2.4. Small Scale biogas Technology

The development of biogas have dated back to ages from the Assyrians in 10 BC when it was used in heating bath water and since that time there have been changes and development to the technology across different timelines (Benveunto and Plaumann, 2022). However, the knowledge of the flammable properties of biogas was further shaped in the 1600's with the observation of flammable gases from swamps and decomposing organic matter, which led to the discovery of methane and the discovery of the anaerobic digestion system (Benveunto and Plaumann, 2022). The discovery of methane can be attributed to the Italian scientist Alessandro Volta in the 1770s (Fabrizzi, 2023). However, what is known as the first biogas digester was constructed in India in 1859 to convert organic waste into biogas at a leper's colony in Bombay (present day Mumbai) (Prasad et al., 2022). Further development saw to the use of biogas from sewage system in Exeter England and used for street lightening (Thomas, 2020). This approach of the use of biogas for street lightening was replicated in Berlin, Germany through the use of sewage waste (Thomas, 2020). Considerably, municipal sewage played a significant role in driving biogas technology during this period (Prasad et al., 2022). This developments and interest in biogas led to the development of biogas technology known as Imhoff tank a two-chambered tank developed by Karl Imhoff, which was a transition from the previous approach to the anaerobic processing of waste (Pillay, 2006).

In Africa, there was a reported increase in the number of digester installed between 2011 and 2012 (Singh and Walia, 2016). However, paucity of data makes it difficult to understand the level of progress made so far in improving biogas use and adoption among households (Dahunsi et al., 2020). Studies (Dahunsi et al., 2020; Chinwe, 2024) have however been able to establish the fact that biogas can potentially improve access to energy among households in Africa. Specifically, Jekayinfa et al. (2020) noted that Nigeria has the potential to produce biogas equivalent to 0.48 million barrels from the use of livestock and when he potential from household waste is included, these value will increase. These shows that the use of biogas has the potential or replacing fossil fuels if the right things are put in place.

These supports can be seen in the program of Netherland Development Organisation (SNV), which has provided support for the installation of biogas in different countries

(Ancalet, 2023). These points to the fact that coordinated efforts has the potential of also ensuring the adoption of biogas among the populace. Globally production of biogas has increased from around 0.29 exajoules to about 1.46 exajoules between the year 2000 and 2022 (Borawski et al., 2024). These shows that considerable progress is being made to ensure the potential of biogas is fully explored while ensuring that biogas technology can easily be adopted by households and communities for their energy needs. The small-scale biogas technology has helped in the expansion of biogas technologies to more rural areas where it is been used for cooking and other energy needs of the households (Lohani et al., 2021).

China, which is one of the pioneering countries in the use of small-scale biogas technology, is reported to be one of the countries with the highest number of biogas plants on a large scale and many household units installed in households (Giwa et al., 2020). China leads globally in biogas adoption and has a significant number of household biogas plants, providing clean energy and nutrient-rich bio fertilisers (Giwa et al., 2020). India has also installed numerous small-scale biogas plants, particularly in rural regions with these plants utilising animal dung and human excreta as feedstock and contributing to energy self-sufficiency (Bhatia et al., 2020). Countries like Australia and the UK also utilise it for the purpose of heat and electricity while in countries like Germany the use is slowing down compared to other countries (Valavanidis, 2020). Germany has a well-established biogas sector, including both small and large-scale plants (Iglesias et al., 2021). These facilities convert organic materials into biogas, reducing greenhouse gas emissions and promoting circular economy principles (Iglesias et al., 2021). In countries like Sweden with advanced waste management practices, progress in the use of small-scale biogas is not as prominent as strides made in larger-scale biogas production from organic waste (Gustafsson and Anderberg, 2023). Australia has been exploring biogas as part of its renewable energy mix while not as widespread as solar or wind energy, small-scale biogas projects are gaining attention (Tait et al., 2021). However O'Connor et al. (2021), reported that countries like the UK are also taking the investment in large scale Biogas plant as a way of managing organic waste much more serious but the use of smaller plants as being proposed in this study has limited usage in the country.

As stated earlier, there is paucity of data on the level of adoption of biogas in Africa but in the last few years, there have been installation of small biogas digesters in rural areas across Asia, South America, and Africa over the last 50 years (Shallo et al., 2020). These digesters convert organic waste, biomass, and animal manure into biogas through anaerobic digestion (Shallo et al., 2020). Nigeria, as part of sub-Saharan Africa, has also explored biogas technology but faced with challenges related to technical skills, awareness, and education persist, there is significant potential for household bio digesters in the country (Tolessa, 2024). According to a study by Ketuama et al. (2022), the technical potential for household biogas plants in Africa is approximately 32.9 million installations, with Nigeria being part of this potential (Ketuama et al., 2022).

2.5. Household Waste Composition

Household waste is generated from the different activities involved in the by the households. The categories of the waste is diverse and the management of this waste can portend a lot for sustainability efforts (Yousafzai et al., 2020). It is important to note that households waste reflects the economic, cultural and consumption pattern of the household. Rosesar and Kristanto (2020), noted that the composition of household waste and its characteristics are important for planning a waste management system. Understanding the composition of household waste can give an overview of how effective a waste management system using biogas can be.

Rosear and Kristanto (2020), conducted a study in Urban part of Indonesia to determine the composition of household waste using cross sectional study. It was discovered that around 61.62% of the waste generated among the urban households was organic waste with inorganic waste making up the rest. Noufal et al (2020) noted that the lack of information on waste composition makes it challenging to manage waste. From the study of Noufal et al (2020), it was also confirmed that household waste was made up of majority of organic materials as the waste composition in Syria showed that organic waste made 69.1% of waste generated while the rest were made up of inorganic materials like plastic, inert materials, paper, textile, metal, glass, wood, and hazardous materials. Villalba et al (2020), in his own study in Argentina to characterise solid waste generated by households using households stratified into three groups based on their socioeconomic status of high, medium and low. The study discovered that the organic waste was the waste generated the most across the entire socioeconomic status stratum. When statistical comparison was done across the strata to see if there was a significant difference in waste generated across the strata. The result showed that there was no significant difference across the strata meaning that the level of organic waste is the same across the strata. This shows that the trend of generation of organic waste is not only applicable to rural areas in Nigeria but has a global dimension.

Studies from Africa like that of Dikole and Letshwenyo (2020), to study the generation rate, composition, and characterise the solid waste generated from low, middle and high income households in a village in Botswana. The study also reported that food waste was the highest composition in the waste generated by the households with around 46% to 80% of the waste generated being food waste. Agwuncha et al (2022), did a similar study on waste composition in Niger state, Nigeria. The study reported that the volume of waste generated was around 93.88 tons per day with waste composed of 44% organic wastes, 26% mixture of sand, ash and dust; and 30% were recyclable matter. A similar study by Adekunle et al (2020) in Ibadan, Nigeria, also found out that organic made up 41.5% of waste generated in the metropolis with plastics making up 21.4%, Paper and paper board 8.4%, textile 3.4%, metal 2.7%, glass 1.9%, and other waste making up the rest. The study noted that that more around 41.8% of the waste was compostable while around 37.9% was found to be recyclable and about 20.3% had no reuse value.

The composition of this waste shows that with the right approach and strategy, households waste can be further managed to get more value from it. Aderoju (2020) however reported a slight variation in her study conducted in Abuja using 939 households, which were stratified into low and high income. The study showed that the level of income and status influenced the type of waste generated. For instance, it was discovered that the high-income households had the lowest percentage of organic waste with paper waste forming their highest waste composition while the low-income households had the highest composition of organic waste. This shows that socioeconomic status could play an important role in the composition of the waste generated by the households. Emeka et al (2021) who also did a study in Port Harcourt, Nigeria observed the waste generated by the city continues to increase over time with more than 90% increase between 2001 and 2021 showing that the issue of waste management waste is a great challenge. The study also reported that food waste, which is an organic form of waste, made up about 44.5% of the waste content while others like paper, plastics, textiles, electrical made up the remaining component. Although many of the studies reviewed suggested recycling of waste as an important means of managing the waste. It is however important to note that while recycling may be a good option for management of inorganic waste like paper, plastic, organic waste which easily decompose are not liable to recycling. This is because of their perishable nature and due to the level of this waste in the composition of household waste, it is best to identify the best alternative to put this waste to use and reduce its potential impact on the environment. This makes the generation of biogas from the waste a plausible option across different locality including Nigeria considering the fact that organic waste makes up the highest composition of the waste generated among the households.

Therefore, based on the papers reviewed so far, it can be inferred that household waste composition varies from one location to the other and can be influenced by factors like income level, consumption patterns, and waste management infrastructure. Globally the largest fraction of waste comes from food waste, which account from between 40 and 60% of waste composition while paper, plastic, glass, metal, textiles, rubber, e-waste, and hazardous waste, contribute the rest (Chen et al., 2020). In Nigeria, household waste is mainly composed of organic waste at around 30 to 60% of waste composition, which is due to reliance on organic foods and limited composting practices (Adekunle et al., 2020). Other components identified in the waste composition of the household is the level of plastic waste which is a growing concern in Nigeria, with its share potentially increasing due to rising consumption and limited recycling infrastructure (Emeka et al., 2021). Paper waste, metal and glass waste among others. This shows that organic waste is a dominant component of household waste in both Nigeria and globally (Adekunle et al., 2020).

2.6. Impact of Household Organic Waste on the Environment

Household organic waste includes food scraps, garden waste, and other biodegradable materials, which has significant environmental impacts when not managed properly (Koul et al., 2022). These impacts can manifest in various forms, from contributing to greenhouse gas emissions to polluting water bodies and attracting pests (Koul et al., 2022). Household organic waste seems harmless, but it can have a significant negative impact on the environment if not managed properly. Household organic waste have been reported to make up the major part of household waste (Atelge et al., 2020). Thus necessitating the need to examine the impact that it has on the environment. However, because of the way that this waste is managed it ends causing negative impact on the environment.

Firstly, household organic waste mainly end up in landfills where it decomposes anaerobically (without oxygen) (Koul et al., 2022). This process generates methane, a potent greenhouse gas with 25 times the heat-trapping capacity of carbon dioxide over a 100-year period (Arif, 2024). These landfills have been found to be responsible for around 29% of global methane emissions as at 2000 and contributing to global warming and climate change (Abdelli et al., 2020).

In addition, improper disposal of organic waste, such as dumping or littering on abandoned lands and in water, can lead to contamination of soil and water resources while the leachate, a liquid produced as organic waste decomposes, can contain harmful bacteria, heavy metals, and nutrients like nitrogen and phosphorus (Adekanmi, 2021). The resultant effect is that the contaminated soil becomes less fertile and unsuitable for agriculture while posing a serious risk for humans and wildlife (Adekanmi, 2021). Also, the leachate can percolate through the soil and contaminate groundwater and surface water sources, posing risks to drinking water supplies and aquatic ecosystems (Ayilara et al., 2020). While it can also have an Eutrophication effect because of the production of nitrogen and phosphorus from the decomposing waste which can escape into water bodies, causing excessive algal blooms, and depletion of oxygen in the water and harming aquatic life (Ayilara et al., 2020).

Furthermore, the open burning of organic waste which is common in many developing countries including Nigeria, releases harmful pollutants like particulate matter, volatile organic compounds (VOCs), and dioxins into the air (Elehinafe et al., 2022). Additionally, the uncontrolled decomposition of the waste can lead to the release of pungent-smelling gases such as hydrogen sulphide (H_2S) and ammonia (NH_3) (Mushtaq et al., 2020). This smell can cause significant public nuisance and affecting the quality of people staying in the proximity of the refuse dumb (Elehinafe et al., 2022). These pollutants contributes to respiratory problems, cardiovascular diseases, and other health issues while open burning contributes to climate change by releasing greenhouse gases and black carbon particles (Elehinafe et al., 2022).

Pest and disease can be harboured as a result of improper disposal of organic waste. This is mainly because organic waste, particularly food scraps attracts pests such as rodents, flies, and cockroaches, which serves as disease vectors (Ayilara et al., 2020). This poses significant public health risks, particularly in urban areas with inadequate waste management systems (Ayilara et al., 2020). Further impact shows that household organic waste contains valuable nutrients for crop growth like nitrogen, phosphorus, and potassium and when not put to effect use like composting or recycling, these nutrients are lost to the environment (Sayara et al., 2020). The inability to effectively utilise organic waste has increased the dependence on chemical/synthetic fertiliser, which are not goof for the environment (Sayara et al., 2020).

As such, it is important to mitigate the negative impact of organic waste by giving consideration for implementing effective household waste management practices to minimise the environmental impact of organic waste. In line with this study, promoting composting and anaerobic digestion technologies can help in converting organic waste into compost and biogas. Through this, it will ensure that the mass of the waste is reduced while also utilising the household waste for the purpose of gas generation to meet household energy needs while the remaining waste is used as plant nutrient.

2.7. Biogas production from household Waste

It is important to note that decisions as regards the environment must be premised on sustainability this is because of the need to ensure the use of the environment in the present does not affect future generation (Czekala, 2022). Therefore, the utilisation of organic household waste for the generation of biogas is a very sustainable means of waste management and clean energy production (Czekala, 2022). The process of biogas production involves the breakdown of organic materials in the absence of oxygen (anaerobic digestion) to produce a biogas, which consists of methane and CO_2 and digestate (a nutrient-rich by product, which can be used as fertiliser) (Poddar et al., 2022).

This starts from the collection of household waste and separation into different components (Poddar et al., 2022). Essentially the important component of waste for the purpose of biogas production are the organic waste such as food scraps, vegetable peels, garden waste, and biodegradable materials (Czekala, 2022). This waste are thoroughly separated from the inorganic waste like plastics, metals and glass to ensure that only organic waste enters the biogas system (Sharma et al., 2020). After separation, the waste size is reduced into smaller surface area to ensure the effectiveness of the microbial action in the anaerobic digestion process (Zamri et al., 2020). After this the organic waste is mixed with water to form a slurry which ensures easier handling of the waste and ensure that enough moisture is available for the digestion process to take place (Zamri et al., 2020).

After the preparation stage for the raw materials, the waste is then fed into the anaerobic digester, which is sealed container that is oxygen free (Sharma et al., 2020). The anaerobic digestion involves four stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Induchoodan et al., 2022). This stage involves different microorganism action and chemical reaction, which then result in the production of the biogas (Lin et al., 2021). The produced biogas is collected in a gasholder or storage tank (Lin et al., 2021). The gas produced is mainly a combination of about 50 -70% methane, about 30 to 50% carbon dioxide and trace amounts of other gases like hydrogen sulphide (H_2S) and water vapour (Sharma et al., 2022).

To ensure that the production process is optimal, temperature must be maintained at a range of 30-40°C (86-104°F), while during the thermophilic digestion higher temperatures of 50-60°C (122-140°F) must be maintained (Lin et al., 2021). Neutral pH is also important to ensure the survival and activity of the different microbial activities (Induchoodan et al., 2022). Mixing is also important in the digester to ensure equal activities and distribution of microbes and to prevent the settling down of solid substances (Yang and Deng, 2020). Other critical parameters that must be monitored include the organic loading rate (OLR) and hydraulic retention time (HRT) to ensure the digester operates efficiently without overloading at any point in time to prevent pressure build up in the digester (Yang and Deng, 2020).

The gas produced in the digester usually accumulates in the upper part of the digester and then collected for different use like cooking, lighting, electricity generation among other uses (Sharma et al., 2022). The sludge or waste material after the anaerobic digestion known as digestate, is a nutrient-rich by-product which can be used as an organic fertiliser to improve soil fertility and crop yields (Lee et al., 2021).

2.8. Anaerobic Digestion Process

There are four main stage of Anaerobic Digestion in the digester and this process the breakdown of organic matter in the absence of oxygen to produce biogas and digestate (Kunz et al., 2022). These stages include hydrolysis, acidogenesis, acetogenesis, and methanogenesis (kunz et al., 2022). In each stage, a biochemical reaction takes place in the presence of microorganism, which serve as catalyst for the reaction (Kunz et al., 2022).

Stage 1: Hydrolysis:

Hydrolysis is the first stage where complex organic polymers are broken down into simpler soluble molecules (Induchoodan et al., 2022). This step is critical because only simpler molecules can be taken up and processed by microorganisms in the subsequent stages (Kunz et al., 2022). Hydrolysis is the breaking down of complex organic polymers (carbohydrates, proteins, and fats) into simpler monomers (sugars, amino acids, and fatty acids) by hydrolytic bacteria (Gupta et al., 2022). Hydrolytic bacteria secrete hydrolytic enzymes like cellulase, proteases, and lipases (Dogam and Taskin, 2021). For instance, cellulose and starch are broken down into simple sugars like glucose while protein is hydrolysed into amino acids and fats broken down into glycerol and fatty acids (Gupta et al., 2022). Hydrolysis is the rate-limiting step of anaerobic digestion because the breakdown of complex organic matter can be slow, particularly for lignocellulose materials (Induchoodan et al., 2022). Organic waste substrates, such as lignin, cellulose, and hemicellulose, may be difficult to breakdown due to their complex structure and as such enzymes are introduced to hasten the process (Induchoodan et al., 2022). One of the important stages of the anaerobic digestion process is the hydrolysis stage and this is because it is the first stage of the process and as such, strict adherence at this stage is important to ensure that the process goes on smoothly (Sharma et al., 2022). The optimum temperature for hydrolysis is between 30–50^{0}C and a pH of 5–7 (Azman, 2016). However, the issue of the optimum pH for hydrolysis is still debatable (Azman, 2016).

Stage 2: Acidogenesis:

Acidogenesis is the second stage of the anaerobic digestion and this stage involves the breakdown of the monomers produced during the hydrolysis phase by acidogenic (fermentative) bacteria into volatile fatty acids (VFAs) like acetic acid, butyric acid, and propionic acid, which are the main products, and by products like alcohols, hydrogen, ammonia and carbon dioxide (Sharma et al., 2022). This stage is the fermentation stage based on the actions carried out at this stage. Acidogenesis provides the necessary substrates for acetogenesis and methanogenesis (Azman, 2016). The accumulation of VFAs is crucial for the next stage but must be balanced to prevent inhibition of the process (Detman et al., 2021). As much as the phase is the fastest, it is also a sensitive phase, which can affect the other phases. This is mainly due to the acidification of the VFA because of the imbalance between acidogenesis and methanogenesis (Lin et al., 2021).

Essentially, in a well-balanced anaerobic digestion process, the rate of VFA production during acidogenesis should be matched by the rate of VFA consumption during methanogenesis (Detman et al., 2021). When VFAs are produced faster than they are consumed by methanogens it leads to an imbalance. The main causes of this include overloading as a result of introducing too much organic material (high organic loading rate) into the digester, leading to VFA accumulation (Detman et al., 2021). Others factors that can cause it include the presence of methanogen inhibitors such as ammonia in high quantity, fast rate of acidogenesis, pH imbalance, temperature fluctuation among others (Lin et al., 2021).

Stage 3: Acetogenesis:

Acetogenesis is the third stage of the anaerobic digestion and at this stage, the acetogenic bacteria convert VFAs and alcohols into acetic acid, hydrogen, and carbon dioxide (Du et al., 2021). This stage acts as a bridge between acidogenesis and methanogenesis and it is the point where the fermented products are refined into a usable form (Lin et al., 2021). At this stage, acetic acid is produced by the oxidation of VFAs and alcohols with the aid of the acetogenic bacteria. For instance, propionic acid and butyric acid are converted to acetic acid, hydrogen, and carbon dioxide (Harirchi et al., 2022). The acetogenic bacteria refine the process by converting some of the VFAs, particularly longer-chain ones, into acetate, a preferred substrate for the final stage (Detman et al., 2021). Hydrogen produced in this stage is used by hydrogenotrophic methanogens in the next stage, preventing its accumulation, which can inhibit acetogenesis (Azman, 2016).

Stage 4: Methanogenesis

Methanogenesis involves the production of the final product of methane and carbon dioxide via the transformation of acetic acid, hydrogen, and carbon dioxide (Sivamani et al., 2021). The microbes at this stage converts the acetate, along with hydrogen and carbon dioxide, into methane (CH4), the main component of biogas (Kofoed et al., 2021). The process involved here include the acetoclastic methanogenesis whereby the acetoclastic methanogens break down acetic acid into methane and carbon dioxide (Kofoed et al., 2021). This pathway accounts for a significant portion of methane production (Detman et al., 2021). There is also the hydrogenotrophic methanogenesis whereby hydrogen and carbon dioxide react together to produce methane and water (Du et al., 2021). Methanogenesis is important for the stabilisation of the digested material and the production of biogas (Sivamani et al., 2021).

The efficiency of this stage determines the overall methane yield of the anaerobic digestion process (Dogan and Taskin, 2021). This process involves the acetolactic methanogenesis and the hydrogenotrophic methanogenesis with the acetolatic methanogenesis process producing about two third of the methane while the hydrogenotrophic methanogenesis produces the remaining one third (Gupta et al., 2022). Methanogenic is a very sensitive stage, the microorganisms at this stage require a higher pH than the other stages, and they have a slower regeneration time when compared to microorganisms at the other stages (Lin et al., 2021).

The common methanogenesis reaction are shown below (Sharma et al., 2022)

Acetoclastic Methanogenesis:

CH3COOH   CH4 + CO2

Hydrogenotrophic Methanogenesis

CO2 + 4H2   CH4 + 2H2O

It is necessary to note that all the stages of anaerobic reaction are interdependent with the products of one stage serving as the substrates for the next stage (Kunz et al., 2022). Hydrogen produced during acidogenesis and acetogenesis must be consumed by hydrogenotrophic methanogens to prevent feedback inhibition of these stages (Kunz et al., 2022).

2.9. Factors Affecting Anaerobic Digestion

2.9.1. Carbon to Nitrogen Ratio

The Carbon to Nitrogen (C/N) ratio is the ratio of carbon to nitrogen in the feedstock of a bio-digester (Alvarez-Montero et al., 2022). The optimal C/N ratio for anaerobic digestion is generally between 20:1 and 30:1 (Rochas-Meneses et al., 2022). This range promotes efficient microbial activity, maximises biogas yield and ensures process stability. A balanced C/N ration ensures that optimal microbial growth and activity, promotes the efficient breakdown of organic matter, maximises biogas production and methane yield (Alvarez-Montero et al., 2022). Regular monitoring and adjustment of the feedstock composition are essential for maintaining the optimal C/N ratio, thereby enhancing the efficiency and stability of the anaerobic digestion process (Rochas-Meneses et al., 2022).

2.9.2. Volatile Solid

Volatile Solids (VS) is the portion of the total solids in a feedstock that is organic and can be decomposed by microorganisms (Zamri et al., 2021). They are a key indicator of the organic matter available for anaerobic digestion (Ziaee et al., 2021). VS is determined by burning a dried sample at high temperatures (550°C) in a muffle furnace (Zamri et al., 2021). The weight loss represents the volatile solids, while the remaining ash represents the fixed solids (Zamri et al., 2021). High VS content means more organic matter is available for microbial degradation, which will lead to higher biogas production (Srivastava et al., 2020).

VS essentially, provides the organic material that anaerobic microorganisms break down to produce biogas (methane and carbon dioxide) while the quantity and quality of biogas produced are proportional to the amount of degradable VS in the feedstock (Srivastava et al., 2020). Not all VS are equally degradable (Zamri et al., 2021). The biodegradability depends on the composition of the VS (e.g., carbohydrates, proteins, fats) and the presence of recalcitrant compounds like lignin (Zamri et al., 2021). However an easily degradable VS lead to faster and higher biogas production, while recalcitrant VS may require longer retention times or may not be fully degraded (Ziaee et al., 2021).

2.9.3. Particle Size

Particle size plays a critical role in the efficiency of the anaerobic digestion process and the production of biogas (Zhong et al., 2022). Smaller particle sizes generally enhance the rate of digestion and biogas production by increasing the surface area available for microbial activity (Zhang et al., 2020). Studies (Liu et al., 2021; Zhang et al., 2020) have shown that smaller particle size provides a larger surface area for microbial attack, and this enhances the hydrolysis stage. During hydrolysis, complex organic polymers (carbohydrates, proteins, and fats) are broken down into simpler soluble molecules. Smaller particle size allow microorganism's better access to the substrate, facilitating more efficient colonisation and degradation and this improved access of microbial activity leads to higher rates of acidogenesis, acetogenesis, and methanogenesis (Liu et al., 2021).

As such, the optimal particle size range for anaerobic digestion is between 1 to 10 millimetres (Liu et al., 2021). This range balances the benefits of increased surface area and microbial access with manageable viscosity (Liu et al., 2021). The particle size can be reduced using mechanical pre-treatment like grinding and milling or shredding, biological pre-treatment like enzymatic hydrolysis and then the use of thermal pre-treatment (Zhang et al., 2020).

Studies have shown that reducing particle size increases biogas yield by enhancing the hydrolysis rate and improving substrate accessibility (Zhong et al., 2022). For example, a study on food waste digestion found that reducing particle size from 20 mm to 2 mm increased biogas production by up to 20% (Okoro-Shekwaga et al., 2020). Also, anaerobic digesters processing agricultural residues with optimised particle size have reported up to 30% higher biogas yields compared to untreated residues (Kaur, 2022).

2.9.4. Moisture Content

Moisture content in a biodigester affects the microbial activity, nutrient transport, and overall efficiency of biogas production (Singh et al., 2020). Maintaining an optimal moisture level is necessary for ensuring the stability and performance of the digester (Kunz et al., 2022). The ideal moisture content for anaerobic digestion typically ranges between 80% and 90% (Kunz et al., 2022). This range provides the necessary environment for microbial activity and nutrient solubilisation (Kunz et al., 2022). Different types of feedstock have varying moisture content requirements. For example, manure and food waste generally have higher moisture content than crop residues or municipal solid waste (Mahmudul et al., 2021).

Well-hydrated substrate with optimal moisture content ensures efficient mixing, preventing the formation of dead zones and enhancing contact between microorganisms and the substrate and this influences the handling and pumping of the substrate (Mahmudul et al., 2021). It is important the feedstock is pre-treated before loading it into the digester by adding water to dry feedstock or removing excess water from wet feedstock through processes like pressing or dewatering (Abubakar, 2022).

2.9.5. Temperature

Temperature influences the performance and efficiency of anaerobic digestion in a bio digester. The process can operate under different temperature regimes, each affecting the microbial activity, biogas yield, and overall stability of the system (Nie et al., 2021). The temperature range of a bio digester include the psychrophilic Range which uses a temperature below 20°C but this range is characterised by slow microbial activity and lower biogas production rates (Ajayi-Banji and Rahman, 2022). However, this temperature range is rarely used due to inefficiencies. There is also the mesophilic range, which uses a temperature of between 30-40°C (Ajayi-Banji and Rahman, 2022). This temperature range is most common for anaerobic digestion; it is optimal for the activity of mesophilic bacteria and provides a good balance between microbial growth and process stability (Nie et al., 2021). The third range is the thermophilic range, which has a temperature of between 50-60°C (Ryue et al., 2020). This range is characterised by higher microbial activity and faster digestion rates, increased biogas production and pathogen reduction, requires more energy for heating and careful management to avoid instability (Ryue et al., 2020). This range is more sensitive to changes in operating conditions and require precise temperature control to maintain stability but it is more effective at reducing pathogens in the feedstock, making the digestate safer for agricultural use (Roch-Meneses et al., 2022).

Some of the critical consideration for the temperature include the fact that proper insulation is necessary to maintain consistent temperatures, especially in thermophilic systems while maintaining mesophilic or thermophilic conditions can be challenging in colder climates without adequate heating and insulation (Ryue et al., 2020). In addition, the process can become unstable due to temperature fluctuations and thus affecting the microbial activity and the level of biogas production (Rocha-Menesis et al., 2022).

2.9.6. pH

The pH level is an important parameter, which affects the breaking down of organic matter and producing biogas (Koniuszewska et al., 2020). Under mesophilic conditions, the optimal pH is 6.8 to 7.2 while for thermophilic digesters the range is around 7.2 to 7.5 (Nsair et al., 2020). However, the pH of the digester varies depending on the phase of anaerobic digestion (Chew et al., 2021). At the hydrolysis phase of digestion, the pH here is slightly lower due to the release of organic acids (Chew et al., 2021). At the acetogenesis phase, the pH can drop further if the production of VFAs exceeds their conversion to acetic acid while at the methanogenesis phase which is pH sensitive, optimal activity occurs around neutral pH because of the less tolerance of methanogens to acidic conditions compared to other process (Chew et al., 2021; Ekstrand et al., 2022).

Some effect of pH include the inhibition of Methanogens, accumulation of VFAs, reduced biogas yield, ammonia Toxicity, microbial inhibition and reduced biogas quality (Koniuszewska et al., 2020). However, natural buffering agents like bicarbonates, carbonates, and phosphates can be introduced to help maintain pH within the optimal range while mixing different types of feedstock with complementary pH characteristics can help maintain a balanced pH (Koniuszewska et al., 2020; Induchoodan et al., 2022).

2.9.7. Hydraulic Retention Time (HRT)

Hydraulic Retention Time (HRT) is the average length of time that the feedstock (substrate) remains in the biodigester. Sufficient HRT ensures that the microorganisms have enough time to break down the organic matter in the feedstock while short HRT may result in incomplete digestion, reducing biogas yield and quality (Makamure et al., 2021). Also, different groups of microorganisms involved in anaerobic digestion have different growth rates and require different retention times to thrive (Mahmudul et al., 2021). Proper HRT supports the sequential activity of anaerobic (Mahmudul et al., 2021). The optimal HRT for a biodigester depends on several factors, including the type of feedstock, digester design, operating temperature, and desired level of treatment (Makamre et al., 2021). Common HRT ranges for different types of anaerobic digesters include the mesophilic Digesters which ranges from 15 to 30 days and the thermophilic digesters which ranges from between 10 to 20 days due to faster microbial activity at higher temperatures (Rochas-Meneses, 2022).

HRT is influenced by the feedstock composition, for instance solid feedstock like manure, agricultural residues may require longer HRT compared to low-solids feedstock like wastewater to achieve complete digestion (Amah, 2021). Additionally, seasonal changes in feedstock availability and composition may require adjustments in HRT to maintain optimal biogas production ((Rochas-Meneses, 2022; Amah, 2021). Digester design may also be a factor in HRT (Amah, 2021).

2.9.8. Organic Loading Rate (OLR)

Organic Loading Rate (OLR) is the amount of organic matter fed into a bio digester per unit volume of the digester per day (Abubakar, 2022). It is typically expressed in terms of kilograms of volatile solids (VS) or chemical oxygen demand (COD) per cubic meter per day (kg VS/m^3/day or kg COD/m^3/day) (Afrianti et al., 2023). OLR is a critical parameter that directly influences the microbial activity within the bio-digester (Afrianti et al., 2023). Maintaining an appropriate OLR ensures that the microorganisms have sufficient organic matter to process without being overwhelmed (Abubakar, 2022). The right OLR maximises the efficiency of the anaerobic digestion process, ensuring optimal biogas production and stability (Abubakar, 2022).

A low OLR in a bio-digester means that there is insufficient organic matter for the microorganisms to process, leading to suboptimal biogas production and low utilisation of the digester capacity, resulting in an underperformance in terms of waste treatment efficiency (Zamri et al., 2021). An optimal OLR ensures that microorganisms have enough substrate to process efficiently, thereby maximising biogas yield and ensures that all stages of anaerobic digestion proceed efficiently with any overloading (Nkuna et al., 2022). OLR also has effect on the quality of effluent produced (Nkuna et al., 2022). However, a high OLR level can lead to incomplete digestion of organic matter and can result in the accumulation of volatile fatty acids (VFAs) and other intermediates, causing acidification and lowering the pH (Zamri et al., 2021).

2.9.9. Mixing

Mixing in the digester ensure the even distribution of microorganisms, nutrients, and substrate, and preventing the formation of dead zones and sludge accumulation (Uddin and Wright, 2023). It also helps to maintain a consistent temperature throughout the digester, for effective microbial activity and prevents the build-up of biogas bubbles within the slurry, which can reduce the efficiency of the digestion process (Uddin and Wright, 2023).

The types of mixing in a digester include the mechanical mixing, which involves the use of mechanical agitators or impellers to stir the digester contents (Leonzio, 2020). This method provides robust mixing but can be energy-intensive and may require maintenance (Leonzio, 2020). There is also the gas mixing whereby the biogas produced in the digester is recirculated and injected at the bottom, creating bubbles that mix the contents as they rise (Singh et al., 2020). This method is energy-efficient and minimises mechanical wear and tear (Singh et al., 2020). There is also the hydraulic mixing with the use of pumps to circulate the slurry through the digester (Leonzio, 2020). Although, this method has been found to be less effective than mechanical or gas mixing but is simpler and requires less maintenance (Singh et al., 2021).

Proper mixing in the digester ensures that microorganisms have consistent access to nutrients, leading to more efficient breakdown of organic matter and higher biogas yields (Singh et al., 2021). It also prevents the settling of heavy particles and the floating of lighter ones, ensuring a homogeneous environment and equal temperature that facilitates better digestion (Singh et al., 2020).

2.9.10. Feedstock

The type and quality of feedstock fed into a bio-digester also influences the efficiency of the anaerobic digestion process and the quantity and quality of biogas produced (Obileke et al., 2021). The common types of feedstock are agricultural residues, which is made up of crop residues, straw, corn stover, animal manure (Amoo et al., 2023). This particular feedstock is high in lignocellulosic content, variable moisture content and has high C/N ratio (Amoo et al., 2023). There is also the food waste (Kitchen scraps, expired food products, food processing waste) which has high moisture content, high organic content, easily degradable but has low to moderate C/N ratio, high biogas yield, rapid acidification potential requiring careful pH monitoring (Okwu et al., 2020).

What affects the quality of the feedstock include the organic composition which is measured by the carbon to nitrogen (C/N) Ratio, the presence of volatile solids (VS), the moisture content of the feedstock, particle size, pH levels, presence or absence of inhibitory substances (Amoo et al., 2023). However, feedstock can be modified using pre-treatments such a reducing particle size, heating the feedstock to break down complex compounds, using chemicals to solubilise lignocellulose materials and increase digestibility and using specific microorganisms to pre-digest feedstock before entering the main digester (Okwu et al., 2020). Co digestion can also be used to improve the feedstock (Obileke et al., 2021).

2.9.11. Digester type

The type of digester used can also significantly affect the quality of biogas that is produced in a digester essentially digester type determine a lot in terms of the type of feedstock, retention time, temperature among other factors (Abubakar, 2022). As such, the digester type can have influence on the biogas produced due to factors like feedstock compatibility, which varies from one digester to the other (Kirk and Gould, 2020). Essentially continuous stirred tank reactor (CSTRs) and anaerobic sequencing batch rectors (ASBRs) are versatile and can handle a wide range of organic materials, while plug flow reactors are better for solid-rich feedstock (Kulichkova et al., 2020). In terms of the retention time and organic loading rate, the design of the digester determine the retention time of the digester (Kulichikova et al., 2020). For instance, CSTRs, allow for continuous feeding and high OLRs, leading to higher biogas production rates (Abubakar, 2020). The mixing is also another factor that distinguish digester types (Kirk and Gould, 2020). This is because digesters with effective mixing, such as CSTRs and ASBRs, tend to have more stable microorganism activities and better process control, resulting in consistent biogas production while simpler designs like fixed-dome digesters are cost-effective and easier to maintain but may produce less biogas due to limited mixing (Abubakar, 2022). However, the more complex designs like UASB and CSTRs require higher initial investment and operational expertise but offer higher biogas yields (Abubakar, 2022).

2.9.11.1. Types of Digester

There are different types of digester that are applicable to the production biogas (Obileke et al., 2021). These include the

2.9.11.1.1 Continuous-flow Stirred Tank Reactor (CSTR)

Continuous-Flow Stirred Tank Reactor (CSTR) is a technology used for biogas production. A tank where feedstock is continuously added and digested material is continuously removed (Ekeng, 2020). Mechanical or gas mixing is often used. The CSTR is a reactor vessel with continuous agitation and mixing (Ekeng, 2020). The biomass fed into the CSTR is constantly mixed, ensuring perfect homogenisation (Shen et al., 2021). Efficient biogas production relies on proper mixing and homogenisation of the biomass. After digestion, the resulting digestate is separated into solids and liquids (Banerjee et al., 2022). The Empirical studies (Banerjee et al., 2022) have modelled and tested CSTRs for biogas production from municipal solid waste. It was discovered that stirring the feedstock (municipal solid waste) improves its potential for biogas production under optimal condition like pH of 7.8, a retention time of 28 days, and an organic loading rate of 8 kg, resulting in a maximum biogas yield of 62.4 mL (Banerjee et al., 2022). According to Shah et al. (2024), the mixing efficiency of the CSTR ensures a good yiled of biogas and makes the technology suitable for different types of feedstock.

2.9.11.1.2 Plug Flow Reactor

A plug flow reactor is a type of anaerobic digester used for biogas production. A plug flow reactor is a long, narrow tank made of reinforced concrete, steel, or fiberglass (Pilloni and

Hamed, 2021). It has a plastic gas-tight cover to capture the biogas. Unlike fixed dome digesters, plug flow reactors have lower biogas pressures. Feedstock moves through the digester in a plug flow manner, with little to no back mixing (Sawale and Kulkarni, 2022). Typically used for more solid feedstock like manure (Sawale and Kulkarni, 2022). They are cheaper to construct and can be built to suit any substrate volume (Sawale and Kulkarni, 2022). This reactor consists of four main parts, which include the digester (bottom Part) where the feedstock is fed, the dome that captures the biogas. It also has an inlet pipe and gas Balloon to collect the produced biogas (Vasilliadou et al., 2023). This reactor is a batch reactor, which allows the reactor to be periodically fed with feedstock (Aggarangsi et al., 2023). The pH of the reactor stabilises around 6.5, and the temperature remains constant (35-40°C during the day and 25-30°C at night) (Pilloni and Hamed, 2021). Biogas production using plug flow reactors offers a sustainable and affordable energy solution, especially in rural areas (Vasilliadou et al., 2023). Farmers can benefit from this simple yet effective technology, which converts organic waste into valuable biogas. The reactor is a simple design with low maintenance (Aggarangsi et al., 2023). It is also efficient for digesting high-solids content, but may have lower biogas yield if mixing is inadequate (Vasilliadou et al., 2023).

2.9.11.1.3 Up flow Anaerobic Sludge Blanket (UASB)

UASB reactors are traditionally used for treating soluble and biodegradable substrates (Rattier et al., 2022). UASB produces less sludge compared to aerobic systems (Engida et al., 2020). Proper pre-treatment increases biogas yield, while post-treatment ensures effluent meets standards (Engida et al., 2020). The technology is good for tropical countries, where limited reactor heating is needed (Rattier et al., 2022).

The UASB uses a process where wastewater flows upward through a dense bed of sludge where anaerobic digestion occurs and gas bubbles help mix the sludge (Madalena et al., 2020). This ensures high treatment efficiency for wastewater, low energy consumption and high biogas yield. It is less suitable for solid feedstock (Mainardis et al., 2020).

2.9.11.1.4 Fixed-Dome and Floating Drum Digesters

The fixed dome biogas digester is an underground structure made of bricks, concrete, or locally available materials. It consists of a cylindrical chamber with a dome-shaped gasholder (Chinwe, 2024). The advantage of this design is that it is simple, easy to construct and maintain, suitable for a wide range of organic materials and cost-effective for small to medium-scale applications (Abubakar, 2022). The dome in the design serves the purpose of gas storage and thus reducing the level of gas leakage (Jameel et al., 2024).

The floating drum digester on the other hand includes a cylindrical underground chamber and a movable gasholder (drum) that floats on the fermentation slurry (Sharma et al., 2022). This method is efficient for gas storage compared to fixed dome digesters and suitable different quantities of organic waste (Obileke et al., 2021). The gasholder in the model rises and falls based on gas production and consumption (Jameel et al., 2024).

The difference between both design is that the fixed-dome digesters has a stationary gas holder, while floating-dome digesters has a gas holder that moves up and down with gas production (Sharma et al., 2022). Both designs are simple, low cost, and suitable for small-scale applications (Jameel et al., 2024). However, the level of mixing can affect the efficiency of the system (Jameel et al., 2024).

2.9.11.1.5 Anaerobic Sequencing Batch Reactor (ASBR)

ASBRs are specialised bioreactors used for anaerobic digestion. They operate in a cyclic manner, consisting of four main steps of feeding the reactor, reaction in the digester, settling and discharge (Chandra, 2022). ASBRs allow efficient anaerobic metabolism, making them suitable for biogas production (Chandra, 2022). A pilot-scale ASBR, seeded with granular biomass, was used to study the anaerobic co-digestion of brewer's yeast and anaerobically treated brewery wastewater.it was discovered that the digester was stable with an organic loading rate of up to 8.0 kg/(m^3·day) and a maximum of 13.6 kg/(m^3·day) in a single cycle (Chen et al., 2020). The specific biogas productivity was over 0.430 m^3/kg of total chemical oxygen demand (COD) with efficiency of over 90% (Li, 2022).

ASBR operates in batch mode, with periods of feeding, reacting, settling, and decanting (Chandra, 2022). Mixing is achieved through mechanical or gas agitation. The model is flexible in operation, with efficient biogas production system (Mutegoa, 2024).

2.10. Basic Components of a Small-Scale Bio-digester for Biogas Production

A small-scale biodigester is designed to convert organic waste into biogas and digestate through the anaerobic digestion process (Kulkami et al., 2021). The efficiency and reliability of the system depend on the proper integration and functioning of several critical components (Kulkami et al., 2021). These key components include

2.10.1. Feedstock Inlet System

This allows the introduction of organic waste into the bio-digester (Sievers et al., 2024). This is important for the purpose of ensuring consistent and controlled supply of organic material and preventing overloading, which can destabilise the digestion process (Sievers et al., 2024).

2.10.2. Digester Tank

This is the main chamber where anaerobic digestion takes place. The tank is usually constructed from materials like concrete, steel, fiberglass, or high-density polyethylene (HDPE) that are resistant to corrosion and chemical reactions (Nasiruddin et al., 2020). The shape of the digester tank can be cylindrical, spherical, or rectangular, depending on the design (Olanocha et al., 2021). Common types include batch, continuous stirred-tank reactor (CSTR), and plug flow digesters (Dabiri et al., 2021). However, the size of the digester tank is usually dependent on the volume of feedstock expected to be processed in bio digester and desired retention time (Nasiruddin et al., 2020). The tank provides an anaerobic environment necessary for microbial activity and efficiency of production (Dabiri et al., 2021).

2.10.3. Mixing System

This system ensure the uniform distribution of microorganisms, nutrients, and temperature within the digester (Singh et al., 2020). The mixing system can either be mechanical mixers, which is made up of propellers, paddles, and agitators, gas mixing system, which is done through the recirculating biogas to mix the contents or pump mixing using pumps (Li et al., 2022). The mixing system prevents the formation of scum layers and sedimentation. It also enhances the contact between microorganisms and substrate (Singh et al., 2020).

2.10.4. Heating system

The heating system maintains optimal temperature conditions for microbial activity (Asim et al., 2022). The heating system is made up of heating Coils/Pipes to provide consistent heating and insulation system to prevent the loss of heat to the environment (Nie et al., 2021). The heating system maintains mesophilic (30-40°C) or thermophilic (50-60°C) temperature conditions, which is necessary for microbial activity and biogas production (Zhu et al., 2022).

2.10.5. Gas Collection and Storage System

The gas collection and storage system collects and stores the produced biogas for later use (Czekala, 2022). This system is made up of the gas Holder/Dome that captures biogas as it is produced, gas storage bag that stores biogas under low pressure, gas pipelines for the transportation of gas to storage or utilisation point and the pressure relief valve for monitoring of pressure to ensure safe pressure limits (Abanades et al., 2022). The collection and storage system prevents biogas losses and ensures a steady supply for energy needs and also ensures safe storage and handling of biogas (Rafiee et al., 2022).

2.10.6. Effluent Discharge System

This removes the digested slurry (digestate) from the biodigester (Mahmudul et al., 2021). This is made up of the outlet pipe/valve and the storage tank/pond where digestate are stored for further use as fertiliser or soil conditioner (Nuhu et al., 2021). This system is quite important because it prevents overfilling of the digester with waste and facilitates the recycling of nutrients (Candido et al., 2022).

2.10.7. Monitoring and Control System

Monitoring and control systems should also be included in the basic components of the biogas system to monitor parameters like temperature, pH, gas production rate, and pressure (Nsair et al., 2020). This would ensure that the system operated at optimal condition while issues with functionality are detected earlier for rectification and to prevent accidents or losses Wu et al., 2021).

2.11. Quantitative Evaluations of the Anaerobic Digestion Process

Evaluating the performance of the anaerobic digestion (AD) process quantitatively is crucial for optimising operations, ensuring process stability, and maximising biogas production (Bhatt and Tao, 2020). Quantitative evaluations involve monitoring key parameters and metrics that provide answers into the efficiency, health, and output of the digestion process (Cruz et al., 2021). The commonly used metrics in the quantitative evaluations of the anaerobic digestion process include the biochemical oxygen demand, chemical oxygen demand, carbon nitrogen ratio, organic loading rate, hydraulic retention time, volatile solid reduction rate (Bhatt and Tao, 2020).

2.11.1. Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) is a measure of the amount of biodegradable organic material present in a sludge (Bezsenyi et al., 2021). This measure is important because it looks at the overall effectiveness of the anaerobic digester (Bezsenyi et al., 2021). BOD is measured over a period of five days at 20°C (BOD), though longer durations can be used for assessments that are more comprehensive (Campa et al., 2021). BOD testing is not usually used because of logistical difficulties, due to time required to complete the test, and the accuracy of information gotten and is therefore unreliable in making judgments with respect to operational adjustments (Sum Parameters, 2018).

The reduction in BOD after AD indicates the extent to which organic pollutants have been decomposed (Yu et al., 2020). As such, the measurement involves measuring the BOD of the feedstock (input material) before it is loaded into the anaerobic digester to determine the organic load and then the BOD of the digestate (output material) after digestion is measured (Pigoli et al., 2021).

The BOD reduction efficiency is the percentage decrease in BOD from the influent to the effluent (Pigoli et al., 2021). A high BOD reduction efficiency indicates effective decomposition of organic matter and a well-functioning anaerobic digestion process (Tamborrino et al., 2021).

$$\text{The BOD reduction efficiency} = \frac{(\text{Influent BOD} - \text{Effluent BOD})}{\text{Effluent BOD}} \times 100$$

BOD is measured in the laboratory using standardised laboratory procedures involving incubation of samples and measurement of oxygen consumption (Pigoli et al., 2021). This involves placing the sample in an airtight container, incubating it for a specified period (usually five days), and measuring the dissolved oxygen before and after incubation (Tamborrino et al., 2021). If the BOD levels are high, this indicates incomplete digestion, and likely adjustments to the system may include reducing the OLR, increasing the HRT, or improving mixing and temperature control to enhance microbial activity (Pigoli et al., 2021).

Variations to the BOD measure include the carbonaceous BOD (cBOD), which is estimated similarly to the BOD but includes a nitrification inhibitor to prevent the oxidation of ammonia, nitrogen, and nitrite (Brose et al., 2023). cBOD is essentially important to provide an accurate measure for organic waste with high protein content thus ensuring that the protein effect is put into consideration (Maal-Bared and Suarez, 2022).

2.11.2. Chemical Oxygen Demand

Chemical oxygen demand (COD) measures the total amount of oxygen required to oxidise organic and inorganic substances in a sample (Hang, 2024). It provides an indication of the organic pollutant load in household waste (Hang, 2024). COD measures both biodegradable and non-biodegradable substances, offering a more comprehensive assessment of the pollutant load unlike Biochemical Oxygen Demand (BOD), which only measures biodegradable organic matter, (Wiyantoko et al., 2020).

The reduction in COD value in a digester usually indicates the extent to which organic matter is decomposed by microorganisms (Maal-Bared et al., 2022). Monitoring COD levels helps in evaluating the performance and efficiency of the anaerobic digester (Maal-Bared et al., 2022). COD reduction is estimated as the percentage decrease in COD from the influent to the effluent (Wiyantoko et al., 2020). COD is measured using methods such as the closed reflux colorimetric method or the closed reflux titrimetric method. In the process, the sample is digested with a strong oxidant (potassium dichromate) in the presence of sulphuric acid and heat (Hang, 2024). The amount of oxidant consumed is proportional to the COD of the sample (Wiyantoko et al., 2024). The final COD value is determined based on the amount of potassium dichromate consumed in the reflux (Kumari et al., 2022). If the COD value is high, it indicates incomplete digestion and the likely adjustments may include reducing OLR, increasing HRT, improving mixing and optimising temperature and pH (Canals et al., 2023).

2.11.3. Relating Measures of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (BOD)

Both the BOD and COD measure the efficiency of the anaerobic digestion process and they give relevant information on the decomposition of the waste (Puig-Castellyi et al., 2020). Although the analysis process for both are different with COD using the dichromate reflux while BOD uses an aerobic bacteria to oxidise the organic material over a five-day period (Chetterjee and Mazumder, 2020).

The BOD/COD ratio provides information on the composition of organic matter in household waste and its biodegradability (Cheong et al., 2022). A high BOD/COD ratio (close to 1) indicates that most of the organic matter is biodegradable; suggesting that biological treatment processes (anaerobic digestion) is very effective (Rocha-Meneses et al., 2022). A low BOD/COD ratio suggests the presence of non-biodegradable organic compounds, indicating that biological processes may not be sufficient for complete treatment (Rocha-Meneses et al., 2022). COD values are generally perceived to be higher than BOD values because COD includes all organic matter, while BOD only includes the fraction that can be biologically degraded within the incubation period. Therefore, high BOD/COD ratios in the influent suggest that the feedstock is rich in biodegradable organic matter, which is favourable for anaerobic digestion while significant reductions in both BOD and COD in the effluent indicate effective organic matter decomposition (Cheong et al., 2022). Thus, BOD to COD ratio gives information on the biodegradable fraction of the sludge in the biodigester (Wei et al., 2023).

2.11.4. Carbon/Nitrogen Ratio

Characterisation of nutrients in the digester is done using the carbon/nitrogen ratio (C/N ratio) (Wang et al., 2017). The major source of Nitrogen in a digester is from the degradation of protein (Choi et al., 2020). The Carbon to Nitrogen ratio (C/N ratio) is the proportion of carbon to nitrogen in the feedstock of an anaerobic digester (Zheng et al., 2021). It is a crucial parameter for the efficient functioning of the anaerobic digestion process (Zheng et al., 2021). The C/N ratio affects the growth and activity of microorganisms involved in anaerobic digestion (Choi et al., 2020). An optimal C/N ratio ensures balanced microbial metabolism and stable digestion (Hao et al., 2022). The ideal C/N ratio for anaerobic digestion is typically between 20:1 and 30:1 (Beniche et al., 2021). This range promotes efficient microbial activity and biogas production (Beniche et al., 2021). When the C/N Ratio is high, it indicates excess carbon, which can slow down the digestion process, reduce biogas production, and result in the accumulation of volatile fatty acids (VFAs), leading to process acidification and instability (Alavi-Borazjani et al., 2020). On the alternative, a low C/N Ratio can lead to the accumulation of ammonia, which can be toxic to microorganisms at high concentrations and ammonia toxicity inhibits microbial activity, reduces biogas yield, and can cause process failure (Alavi-Borazjani et al., 2020).

To measure the C/N Ratio, samples of the feedstock (input material) are collected for analysis (Bednik et al., 2022). These samples can include agricultural residues, food waste, manure, or a mixture of different organic materials (Bednik et al., 2022). The Carbon Content is determined using methods such as elemental analysis (e.g., CHNS analyser) or combustion methods where organic carbon is converted to CO_2 and measured (Li et al., 2020). The Nitrogen content is determined using the Kjeldahl digestion, which measures total nitrogen, or Dumas combustion method, which also converts nitrogen to nitrogen gas (N_2) for measurement (Gautam et al., 2023).

When the C/N Ratio is high, it means that more nitrogen-rich materials needs to be added to the feedstock while a low C/N Ratio implies that carbon-rich materials need to be included in the feedstock (Chen et al., 2020). However, the composition of the feedstock should be managed to achieve the optimal C/N ratio. Maintaining an optimal C/N ratio of around 20:1 to 30:1 ensures that digestion process is efficient and stable (Rocha-Menses et al., 2022). A study done to examine the C/N ratio of dairy manure; found that when there was a high C/N ratio the level of methane concentration in the produced biogas reduced, but an optimum methane production was obtained a C/N ratio of 25:1 (Ajayi-Banji et al., 2020). To ensure a balanced C/N ratio, the attention has been about co-digestion of substrates by combining Nitrogen rich substrate with carbon rich substrate so as to ensure a balance process (Gonzalez et al., 2022). For instance, straw is co-digested to prevent ammonia inhibition (Gonzalez et al., 2022). This is because of the high content of carbon in straw which is around 80: 1 (Gonzalez et al., 2022). Thus, combination of straw with diary manure and chicken manure can help in balancing the C/N ratio (Mahuyodin et al., 2021). However, studies have shown that optimal methane production and reduced ammonia inhibition can be obtained at C/N ratio of 25:1 for mesophilic digesters while for thermophilic digesters the optimal C/N ratio is 35:1 (Ryue et al., 2020)

3. 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.

Therefore based on the outlined main objective the following specific objectives would be achieved in the study;

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

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

4. Methods

4.1. Description of the study area

The study area for the study is Abuja, which is the Federal Capital Territory of Nigeria. The study area is bounded in the west and North by Niger state and to the east, it is bounded by Nasaraw state. Other states that are in proximity to the FCT include Kaduna (Northeast), Kogi (southwest). Additionally the confluence of the river Niger and Benue, which is a tourist attraction, is located to the North of the FCT.

Based on its location, the FCT is located at a geographic position that is at the centre of the country with the latitude being 8.25^0 and 9.20^0 north of the equator while the longitude of the location is 6.45^0 and 7.39^0 east of the Greenwich Meridian. The FCT has a land area of about 7,315 km^2 with the vegetation synonymous of the savannah region and the climatic conditions moderate to support a wide range of crops. In addition, it has six 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).

4.2. Waste Sample Collection and Handling

4.2.1. 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 waste was 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.

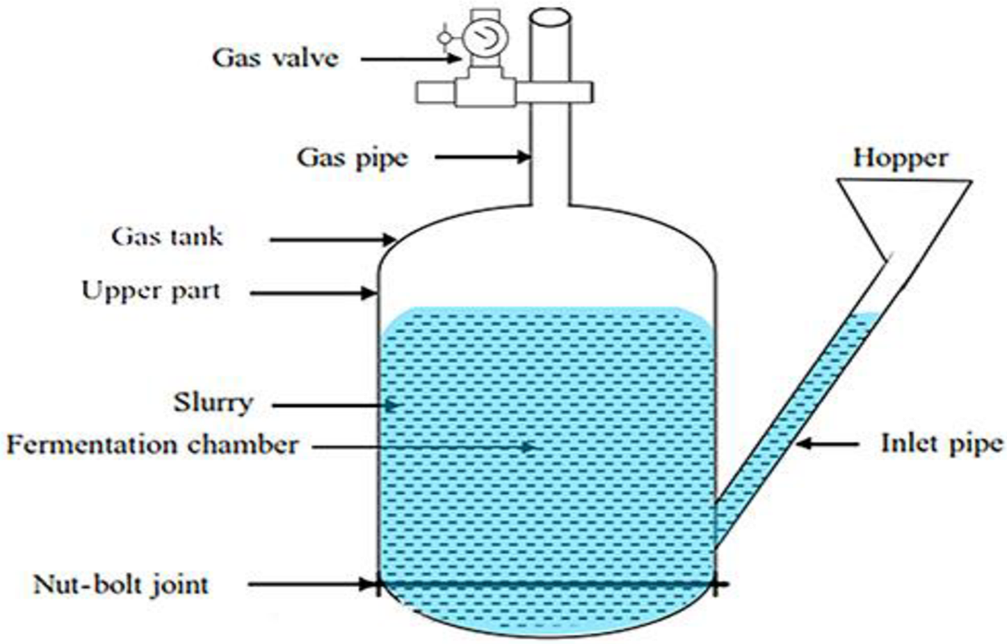

Figure 1. A simple system for Biogas Production

4.3. Materials for Biogas Production

The components of a biogas producing system (figure 1) are as follows:

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

This comprises a container for the unprocessed, fresh organic waste and a minimum 10-cm-diameter pipe that leads to the digester. There must be an airtight connection between the digester and the intake pipe.

(b) **Digester**

This is the organic waste reservoir where anaerobic bacteria act on the substrate to create biogas.

(c) **Gas Storage /Reservoir**

This might be as simple as an airtight polythene tube with an input and outflow fitting, an inverted floating drum with a diameter marginally less than the cylindrical digester, or just an empty but enclosed chamber above the slurry in the digester, depending on the planned design.

(d) **Gas Burner**

This could be an altered hob intended for cooking or a customised illumination lamp.

(e) **Exhaust outlet**

To enable the outflow of exhausted slurry, this comprises of a pipe that is linked to the digester at a level that is marginally lower than the inlet pipe and is of a size comparable to the inlet pipe.

Every material used was obtained locally (GTZ, 2011).

4.3.1. Production processes

Any organic material can be converted into biogas through three major steps of anaerobic fermentation. In order to make biogas, organic wastes must go through three phases of anaerobic fermentation:

1. **First Stage**

At the first stage, hydrolytic and fermentative bacteria attack complex organic substances by releasing enzymes and fermenting hydrolysed chemicals into hydrogen and acetate. Only a little portion of the carbon will be converted to volatile fatty acids, mostly butyric and propionic acids.

2. **Second Stage**

During the second stage, the volatile fatty acids are transformed into acetate and hydrogen-by the acetogenic bacteria aiding the decomposition process.

3. **Third Stage**

Acetate and hydrogen are transformed into methane by microorganisms that produce methane. The fact that distinct microorganisms function on various substrates indicates a certain level of specialisation. The subsequent factors need to be carefully balanced in order for these microorganisms to function as intended and produce the intended output.

(i) The substrate dilution, or the volume of water needed to dilute the waste.

(ii) 350 degrees Celsius should be the ideal temperature.

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

(iv) The digester's feeding rate (overfeeding may cause volatile fatty acids to build up; Ludwig et al., 1991, Ludwig et al., 1998).

4.4. Chemical determination of agricultural wastes.

The chemical characteristics of the air-dried household wastes were ascertained by taking into account the total weight of the organic waste that were utilised (FAO, 2008).

4.4.1. Determination of pH of Household waste.

Every beaker was filled with carefully measured household garbage and 100 millilitres of water that was distilled (the sample to water ratio was 1:4). After 30 minutes of heating, it was shaken. It was filtered and chilled. Using a digital pH meter, the pH of the filtered content was measured.

4.4.2. Determination of total nitrogen using Kjeldahl method

The total Nitrogen was determined using each sample weighing 0.5 g, and one gram of catalyst added to each 600 mL digestion tube. It heated gradually until the foaming stopped. After taking the flask off the heater to cool, distilled water was added, and it was then transferred to the appropriate volumetric flask. 20–25 millilitres of 2% boric acid was added to the receiving conical flask. Methyl red indicator was applied in two to three drops. Enough water was injected to cover the condenser outflow tube's end. After adding 5 mL of 40% NaOH and 5 mL of an aliquot pipette to the distillation tube, the ammonia was distilled for approximately 4 minutes. After removing the receiving flask, a tiny amount of distilled water was used to clean the exit tube into the receiving flask. 0.02 NH2SO4 was used to titrate the excess acid. Use the same method to find the blank reagent.

4.4.3. Determination of total phosphorus using Molybivanado phosphoric acid method

To determine the total phosphorususing the molybivanado and phosphoric acid method using a 50 mL volumetric flask, pipette 5–25 mL of the aliquot, depending on the P concentration. Then, add 5 mL of Barton's Reagent and dilute with 50 mL of distilled water. Measure at 420 nm using a spectrophotometer after an hour.

4.4.4. Determination of potassium, calcium and magnesium by using atomic absorption spectroscopic method

The Atomic Absorption Spectroscopic Method (AAS) was used to evaluate the potassium, calcium, and magnesium content of household wastes.

4.4.5. Determination of organic matter

One can determine the Organic Matter (OM) directly by measuring the weight loss upon igniting. A appropriate weight (0.5–1.0 g) of the sample is placed in a silica crucible and heated in a muffle furnace for 4-6 hours to achieve an ash temperature of 500–600°C.

4.5. Data collection

The anticipated daily production of gas will not be assessed due to certain problems. 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).

5. Results and Discussion

Table 1 shows the result value of the different parameter that were measure before and after the anaerobic digestion of the household waste. From the table, it can be deduced that there was a significant statistical difference in the organic matter and carbon content of the waste before and after digestion of the waste. Although other parameter showed either increase or decrease in the before and after value but the values were not statistically different from each other.

Table 1: 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

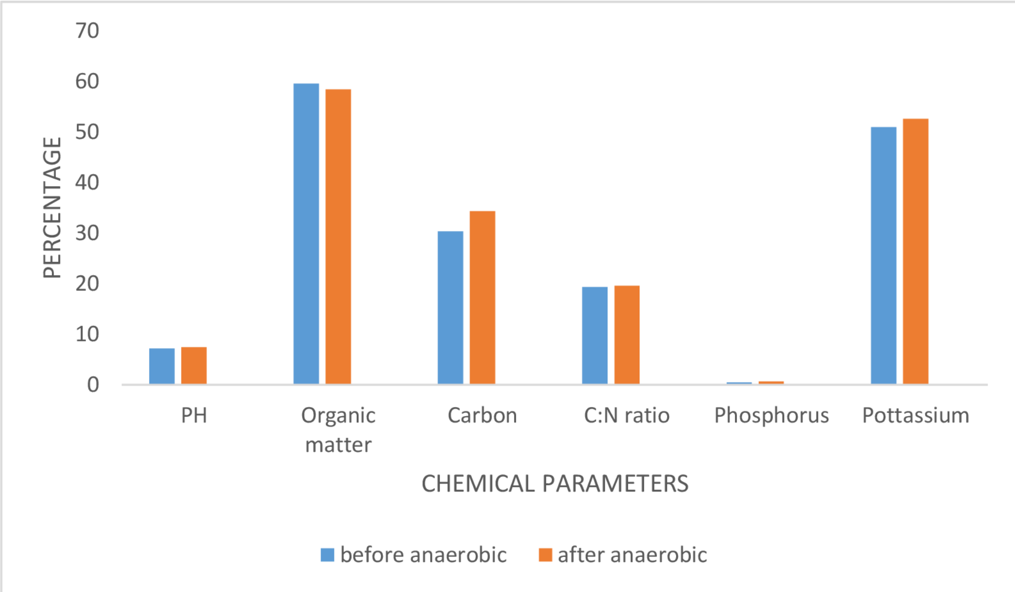

Figure 2: Average value of chemical parameters of household waste before and after anaerobic digestion.

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 reported an increased pH values of 6.6 from 5.5 during the anaerobic digestion of food waste. The final pH value implies 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 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

Organisation (FAO) re-emphasised the soil amelioration potential of bio-slurry, noting its capacity to neutralise 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 what 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 stabilised 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 fertiliser, 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 fertiliser, 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 fertiliser. 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.

Table 2. 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 2 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. Household waste from 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.

5.2. 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 influencing 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.

5.3. 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 favourable 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.

5.4. 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.

5.5. 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.

5.6. Progressive Increase in Biogas Production with Cooking Time

Table 2 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 across the different cooking times. The implication is that biogas production increased with increasing cooking time until it reached the highest value of 43.3g at 360 seconds.

As the cooking time increased from 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.

5.6.1. 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 emphasises 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.

5.6.2. Implications for Biogas Production Optimisation

Understanding the impact of cooking time on biogas production has practical implications for optimising 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 maximise 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 utilisation for biogas production. Efficient utilisation 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, which indicates 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.

5.6.3. 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 periods. This steady increase is indicative of the continuous and effective conversion of organic waste into biogas, highlighting 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 optimising 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.

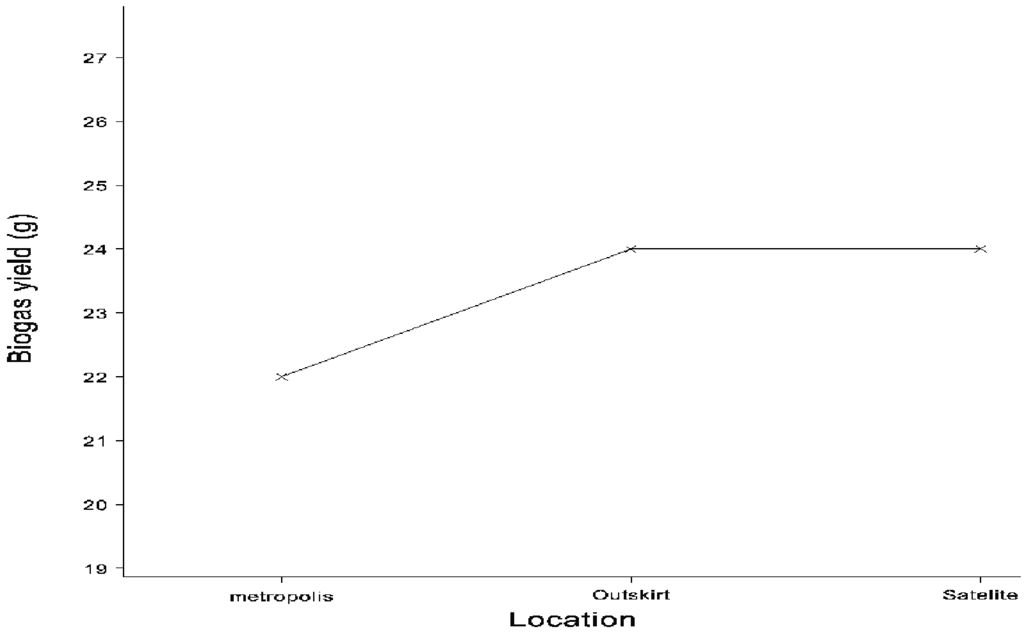

Figure 3. Elaborated values of biogas produced from household waste of different locations.

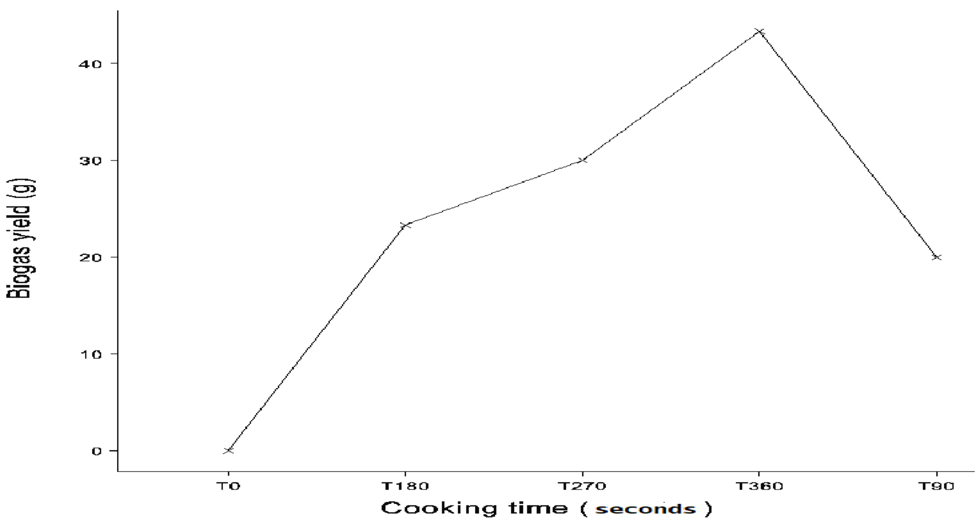

Figure 4. Biogas produced from household waste in seconds

The process of anaerobic digestion is a suitable method for treating municipal solid waste in order to produce additional bioenergy. It is a suitable procedure for handling 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 24.1g, followed by the outskirt with a value of 24.0g and metropolis (22.0g) respectively (figure 3). According to research, there is enough waste (100 kg/day) to produce 24 m3 of biogas per day, which can replace wood fuel and liquid petroleum gas (Ogur and Mbatia, 2013). The amount of biogas produced may be attributed to the waste materials' composition from various sources.

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 and 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. Additionally, 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.

Due to the low decomposition speed and extended retention period, psychrophilic conditions have been the subject of a few studies; however, even though the two-step psychrophilic digester has advantages (Rusín et al., 2020), it is more expensive and takes more room. In contrast, co-digestion of two or more substrates has been shown to be an effective way to preserve pH (Gao et al., 2021), lower VFA accumulation (Cheng et al., 2021), inhibit ammonia (Begum et al., 2021), and improve AD performance in high TS, which in turn enhances methane production. Finding the right ratio for different feedstock can be challenging because the ideal feedstock mix depends on a number of factors, including feedstock type, composition, concentration of trace elements, and biodegradability, among others (Karki, et al., 2021). Moisture and other environmental conditions have an impact on energy recovery, even though a common ratio like C/N has been shown to do so (Cheng et al., 2021). Furthermore, pre-treatment techniques can effectively preserve pH levels (Gnaoui et al., 2020) and increase methane production (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.

Anaerobic digestion is more prone to the negative effects of by-product inhibition, such as ammonia and VFA, which can lead to system failure and adverse effects on the process. For stability of process and biogas production, it can be beneficial to monitor and modify factors like temperature, pH, OLR, TS (%), and C/N ratio. Additionally, some important characteristics that are not addressed in this study are the percentages of soluble COD, TVFA/alkalinity ratio, substrate/inoculum ratio, and volatile solid removal (VSR) (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.

6. 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 determine 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 polarising 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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