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Assessing the Potential of Cassava Waste as a Feedstock for Biogas Production: Case Study Ilaro Nigeria

MASTER'S THESIS

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Declaration

I hereby declare that I have done this thesis entitled Assessing the Potential of Cassava Waste as a Feedstock for Biogas Production (Case Study Ilaro Nigeria).

independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged using complete references and according to the Citation rules of the FTA.

In Prague April 25, 2024.

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Ilo John Oluwatosin

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Abstract

This research investigates the biogas yield of cassava waste and examines socio-economic characteristics, current waste management practices, awareness of biogas potential, and stakeholders' perceptions. The study was carried out in Ilaro, Ogun State, Nigeria, involving surveys, waste management assessments, and biogas production experiments. Results reveal a diverse range of waste management practices, with burning being prevalent despite environmental concerns. However, there is growing awareness of sustainable alternatives, such as selling waste and using it as animal feed. The study also highlights challenges that include inadequate infrastructure and knowledge gaps. Stakeholders express strong support for biogas adoption, but cite financial barriers and lack of technical know-how as challenges. In the biogas yield experiment, exponential growth and microbial adaptation were observed, followed by a decline possibly due to substrate depletion. The results indicate that moderate inoculum levels yield optimal biogas production, while excessive inoculum can be detrimental. The decrease in total and volatile solids over time suggests organic matter breakdown, supporting biogas production. In general, the study underscores the importance of promoting sustainable waste management practices and overcoming barriers to the adoption of biogas for environmental and economic benefits.

Keywords: Biogas, Methane, Inoculum, Adoption, Cassava waste, Waste management, Total solids, Volatile solids, Nigeria.

Table of contents

List of tables

List of figures

1. Introduction

1.1. Background of the study

Energy is critical to the socioeconomic development of a country. In Sub-Saharan Africa (SSA), biomass, mostly fuelwood and charcoal, accounts for around 74% of total energy consumption, compared to 37% in Asia and 25% in Latin America (Amigun et al. 2012). People in SSA do not have access to clean, economical, reliable, safe, and environmentally friendly energy; therefore, they rely on solid biomass to satisfy their basic cooking needs (Brown 2006). This is a significant factor in poverty and a barrier to progress. Half a billion people in SSA live without electricity and rely on solid types of biomass (fuelwood, agricultural residues, animal waste, etc.) to provide their basic energy needs for cooking, heating, and lighting. The problems of these conventional fuels are numerous: (1) they are inefficient energy carriers with difficult to regulate heat release, (2) they emit toxic gases, and (3) their current extraction rate is unsustainable (Parawira 2009).

The growing cost of petroleum products is another major issue for most developing countries, including Nigeria. The overwhelming energy demands of rural and urban residents signal that new natural energy sources must be investigated. As a result, the conversion of agricultural waste to biogas might provide a solution to some of these energy issues. The creation of biogas is a complicated biochemical process that occurs in the absence of oxygen and in the presence of very sensitive microorganisms, primarily bacteria. Anaerobic digestion (AD) has been extensively used throughout the world to recycle organic waste (biowaste) and create biogas to generate electricity, both on a local scale (home biogas generating tanks) and on a large scale (biogas power plants).

According to the European Biogas Association (EBA 2019), at the end of 2017, biogas production had reached 200 TWh a-1 (terawatt-hour per year), accounting for 4% of the onshore gas consumption in the EU. Furthermore, biogas produced more than 65 TWh of European energy in 2017, which is equivalent to Austria's annual power consumption (EBA 2019). In addition to biogas, the by-product, the AD process slurry, known as digestate, can be returned to the soil and used as fertiliser due to its high residual organic carbon content and nutritional richness (Alburuerque et al. 2012; Pawlett et al. 2018). In many regions, agricultural waste, from animal manure to crop residues, is used as raw materials for biogas generation. Cassava solid wastes, as well as other plant wastes have been utilised.

Cassava (*Manihot esculenta*) is a primary staple crop produced by most smallholder and subsistence farmers in Nigeria. Cassava, also known as "bread of the tropics," "food of the poor" or "poverty fighter" by many, is a major source of carbohydrates in tropical Africa due to its resistance to drought and its ability to grow in almost all types of soil, including marginal soils (Coker et al. 2015; Otekunrin & Sawicka 2019). It is a famine reserve crop because, since it is not a seasonal crop, it enables subsistence farmers with limited resources to adjust their harvesting schedule (Stone 2002). Cassava tubers can be processed into a variety of high-calorie meals, including garri (toasted granules), fufu (fermented cooked paste), tapioca (kpokpo-garri flakes), and various confectioneries (Coker et al., 2015). Roots from some low-cyanide cassava species can even be cooked and consumed without additional processing (Oghenejoboh 2012). The many components of cassava make it a particularly suitable low-cost and high-calorie diet for many impoverished Nigerians (Morgan & Choct 2016).

Cassava processing creates significant amounts of solid and liquid waste. Cassava production and processing waste includes leaves, stems, peels, wastewater, and starch bagasse (Oghenejoboh 2015). Farmers in Nigeria typically dispose of generated waste indiscriminately in water bodies, unfinished buildings, undeveloped plots of land and any open space available along major roads and streets, despite the negative impact on both the environment and general health of the people (Oghenejoboh 2015). In Nigeria, the lack of efficient and implementable cassava waste management laws makes it difficult for peasants and smallholder farmers to see the relationship between waste treatment cost efficiency and the value added advantage of cassava waste management. FAO (2020) refers to this ignorance as a knowledge gap. Another key factor is that good waste management is much beyond the capabilities of smallholder farmers, who typically grow and prepare cassava for food and a modest family income (Ekop et al. 2019; Omilani et al. 2019). Therefore, it is necessary to explore other measures to manage waste that accrues from the process in order to ensure good environmental management practices within the processing communities.

Almost all developing nations, including Nigeria, have challenges with waste management. Cassava peels can be used as feedstock for biogas generation rather than being discarded indiscriminately. Cassava peel may also be mono-digested and co-digested. Co-digestion of cassava peel with animal waste such as cow dung, pig waste, chicken droppings, and so on has been proven to create more biogas than digestion of cassava peel alone. Biogas is a colourless and combustible gas that comprises 50-75% methane (CH_4), 25-50% CO_2, carbon dioxide 0-10% nitrogen (N_2), 0-1% hydrogen (H_2), 0-3% hydrogen sulphide (H_2S) and 0-2% oxygen (O_2).

1.2. Objectives

The general objective of this study is to investigate the potential of cassava waste as a feedstock for biogas production in Ilaro, Nigeria.

The specific objectives are to:

1. Evaluate the current practices and challenges in the management of cassava waste in Nigeria
2. Assess the awareness and knowledge of farmers, processors, and other stakeholders regarding the potential of cassava waste for biogas production
3. Determine the attitudes and perceptions of farmers and processors towards the adoption of biogas production from cassava waste
4. Identify the potential barriers and constraints to utilizing cassava waste as a feedstock for biogas production
5. Assess the biogas yield of cassava waste

2. Literature review

2.1. Anaerobic Digestion (AD)

Anaerobic digestion (AD) is a complex process in which practically any form of organic waste can be biologically digested in anaerobic settings by a variety of bacteria consortiums, resulting in mixed gases with significant energy potential known as biogas (Lastella et al., 2002). AD can be performed by digesting a single kind of substrate (mono-digestion) or by concurrently digesting two or more distinct substrates (co-digestion) (Zhang et al. 2016). Anaerobic digestion is a popular and ecologically beneficial biological method to convert and treat complicated biomass and hazardous wastes. In the absence of oxygen, the microbial breakdown of complex organic matter produces an energy-rich substance known as "biogas." Biogas is primarily a combination of methane (CH_4) and carbon dioxide (CO_2), with small amounts of H_2S, ammonia (NH_3), and moisture.

2.2. Stages of the anaerobic digestion process

The anaerobic digestion of biomass has four stages that convert organics into methane gas and other chemicals (Maintinguer & Pires 2016; Schnürer & Jarvis 2018; Laiq Ur Rehman et al. 2019). According to Maintinguer and Pires (2016), the first of these stages is the hydrolysis phase, in which fermentative bacteria hydrolyse and breakdown complex chemical compounds such as fatty acids, glucose, and amino acids (Figure 1). Second, acidogenesis is the phase in which the hydrolysation products of the preceding phase are further degraded into smaller organics such as acetate, butyrate, and propionate, as well as some gaseous compounds such as ammonia (NH_3), carbon dioxide (CO_2) and hydrogen sulphide (H_2S). Third, acetogenesis is the process by which organic products are degraded into chemicals such as acetate, molecular hydrogen (H_2), and CO_2, which are subsequently used in the subsequent phase. Fourth, methanogenesis is the last phase in which the products of the preceding phase are turned into methane gas and other products and by-products (Figure 1).

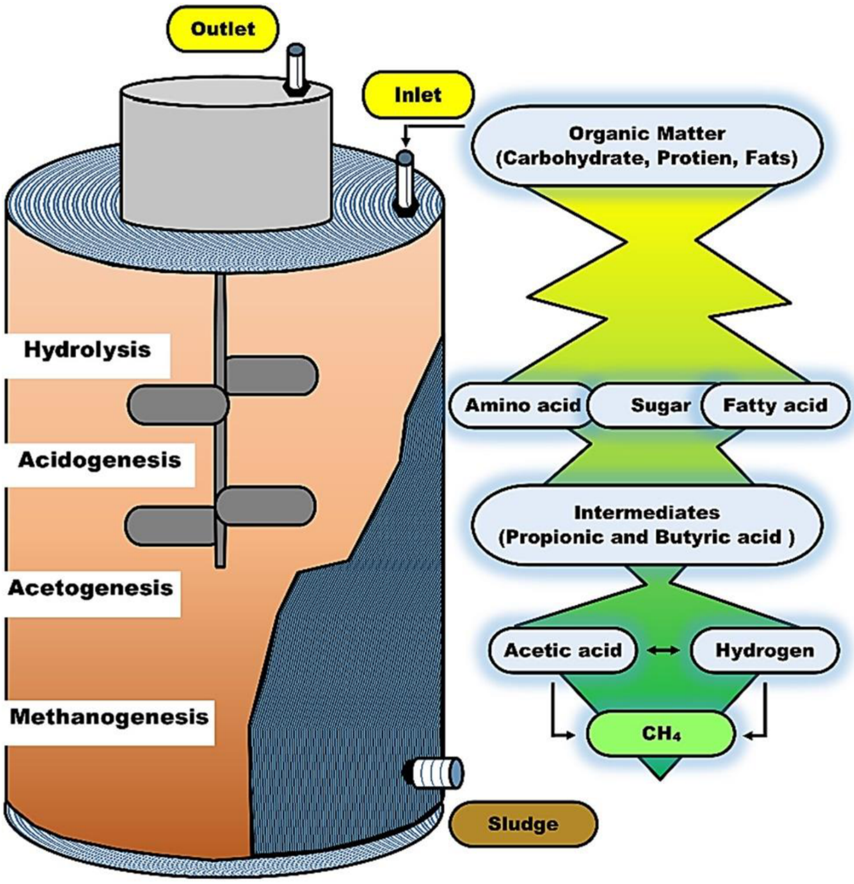

Figure 1: Stages of the anaerobic digestion process

Source: Laiq Ur Rehman et al. (2019)

2.2.1. Hydrolysis

Anaerobic hydrolytic bacteria are found most often in natural habitats such as soils, sewage, animal rumen, compost, and AD sludge. Hydrolytic bacteria use their various hydrolytic enzymes to break down complex polymers (carbohydrates, protein, and fat) into simpler soluble monomers (sugar, amino acid, and long-chain fatty acid) (Castellano-Hinojosa, Armato, Pozo, González-Martnez, & González-López, 2018). The degradation process begins with the creation of a "cellulosome," a multi-enzyme complex form formed by hydrolytic bacteria for the breakdown of organic substrates, in which several hydrolytic enzymes such as glucanases, hemicellulases, chitinases, and liganases are released. Complex bonds are established between bacteria, enzymes, and substrates in cellulosomes, and covalent bonds of substrate polymers are cleaved in a chemical process in the presence of H_2O. Normally, facultative anaerobes use O_2 dissolved in water, resulting in the low redox potential required for obligatorily anaerobic hydrolytic bacteria (Fan, Wnag et al., 2018; Fan, Bi et al., 2018). The degradability of various polymers depends on the nature, content, and complexity of the polymer; for example, hydrolysis of carbohydrates occurs within a few hours, but hydrolysis of proteins and lipids may take several days. Similarly, lignocellulose and lignin breakdown is slow and incomplete (Mulat and Horn, 2018; Schroyen, Vervaeren, Raes, & Van, 2018; Takizawa, Baba, Tada, Fukuda, & Nakai, 2018). Hydrolytic bacteria cannot manufacture enzymes in the absence of a cellulosome.

Furthermore, hydrolytic bacteria found in AD are divided into five phyla: Firmicutes, Bacteroidetes, Fibrobacter, Spirochaetes, and Thermotogae (Batstone et al., 2018). Firmicutes and Bacteroidetes, on the other hand, are the most numerous taxa of hydrolytic bacteria in AD. The relative abundance of hydrolytic bacteria is primarily determined by the kind of inoculum, operational temperature, cell retention time (CRT), and substrate (Wang, Hawkins et al., 2018; Wang, Shen et al., 2018). Other factors that restrict hydrolytic bacteria activity include high build-up of VFA and LCFA, elevated H_2 partial pressure, and humic acid (Di Marcoberardino, Foresti, Binotti, & Manzolini, 2018; Kofoed et al., 2018; Li, Hao, van Loosdrecht, & Luo, 2018). Such inhibition results in permanent deformation of enzyme complexes (due to changes in enzyme chemical structures) or temporary reduction in hydrolysis due to inhibitor binding to enzyme active sites or substrate-enzyme complexes (Angelidaki et al., 2018; Wang, Shen et al., 2018; Wang, Hawkins et al., 2018). Various investigations on the influence of VFAs, LCFAs, high hydrogen partial pressure, and humic acid on hydrolysis have previously been described; however, very few studies have been identified in the current literature. Batstone et al. (2018) investigated the inhibitory impact of humic acid on hydrolysis (carbohydrates and proteins) and acetotrophic methanogenesis. Research found that HA concentrations of 5 g/HAL or above decreased the hydrolytic activity of cellulose, while protein hydrolysis and acetotrophic methanogenesis were the least affected.

2.2.2. Acidogenesis

Hydrolysis products, such as sugar, amino acids, and long-chain fatty acids, serve as substrates for acidogenic bacteria during this stage. These bacteria then breakdown the substrates into short chain organic acids, which mainly comprise C1-C5 carbon molecules. This step results in the formation of organic acids such as butyric acid, propionic acid, acetate, and acetic acid, as well as the release of other molecules such as alcohols, hydrogen, and carbon dioxide. Normally, the concentration of the intermediately formed hydrogen ions influences the type of fermentation products; that is, the higher the hydrogen partial pressure, the fewer reduced compounds (acetate) are formed, and vice versa (Oh, Kang, & Azizi, 2018; Westerholm, Müller, Singh, Karlsson Lindsjö, & Schnürer, 2018; Zhou, Yan, Wong, & Zhang, 2018).

In general, AD has two types of acidogenic bacterial communities: facultative anaerobic acidogens and obligatory anaerobic acidogens. The initial stage of anaerobic digestion is carried out by facultative anaerobic acidogens, whereas obligatory anaerobic acidogens are active in the latter stages. Importantly, acidogenic bacteria are mostly members of the Firmicutes, Bacteroidetes, Proteobacteria and Actinobacteria phyla, while the majority of the bacterial species found in AD according to their abundance during the high fermentation period, confirming their role in this phase, are Clostridium (Firmicutes), Peptococcus (Firmicutes), Bifidobacterium (Actinobacteria). Various operational characteristics and conditions, such as digester design, temperature, cell retention period, and substrate type, may all influence the number and population of acidogenic bacteria in AD. Among all other factors, substrate composition and concentration are thought to be the most influential and have been reported by many researchers; for example, a mesophilic syntrophic acetate oxidising bacterium (Syntrophaceticus schinkii spp.) was significantly enriched by acetate substrates during AD (Cai, Wang et al, 2018; Zhao, Westerholm et al, 2018; Zhao, Ji et al, 2018). Clostridium spp., a bacterium that degrades cellulosic waste, was also shown to be prevalent in high cellulose substrate (Liu, 2018; Silva Rabelo, Soares, Sakamoto, & Varesche, 2018; Zou, Ye, & Zhang, 2018).

2.2.3. Acetogenesis

Acetogenesis, the third step, is the metabolism and transformation of organic acids (propionic, butyric, and pentatonic acid) and alcohols into acetate. Two different groups of acetogenic bacteria use different mechanisms to produce acetate (Wang, Shen et al., 2018; Wang, Wang et al., 2018; Wang, Hawkins et al., 2018). The first kind of bacteria is known as homoacetogenic bacteria because they continuously convert H_2 and CO_2 to acetate. For example, during ethanol fermentation, carbon dioxide and hydrogen are used to produce acetate; If the partial pressure of H_2 increases due to hydrogen accumulation, the activity of acetate-forming bacteria ceases, resulting in loss of acetate production (Fu et al., 2018; Fu, Luo et al., 2018).

Normally, hydrogenotrophic methanogens outperform such processes because they are less advantageous in the AD process. Hydrogenotrophic methanogens, on the other hand, use hydrogen to produce methane, which reduces the hydrogen pressure. However, hydrogenotrophic methanogen activity is crucial for maintaining a low partial hydrogen pressure in AD (Di Marcoberardino et al., 2018; Kofoed et al., 2018). Many acetogenic bacteria of the genus Syntrophomonas (e.g., *Syntrophobacter wolinii* and *Syntrophomonas wolfei*) can also make acetate from other organic acids and are known as "syntrophic fatty-acid oxidising" microorganisms. The conversion of volatile fatty acids (VFAs) into acetate also relies on the partial hydrogen pressure, which must be extremely low for the effective conversion of VFAs into acetate. Any modification in this interaction will result in VFA build-up in the system, affecting overall AD performance.

Syntrophic acetate oxidising bacteria (SAO) are rarely found in the acetogenic stage; such bacteria generally stabilise the AD process, especially when the process is subjected to environmental variations. For example, in the presence of high levels of ammonia, VFAs, heavy metals, and sulphide, SAO converts acetate to H_2 and CO_2, which are typically eaten by hydrogenotrophic methanogens for methane synthesis. The drop in acetate content promotes the activity of acetoclastic methanogens, which contribute more than 70% of methane generation when the digester pH increases (Algapani et al., 2018; Kofoed et al., 2018). There have been reports of both mesophilic and thermophilic SAO in AD, including *Pseudothermotoga lettingae*, *Thermacetogenium phaeum*, *Syntrophaceticus schinkii*, and others in the Spirochaetes phylum (Jiang et al. 2018; Jiang, Ru et al., 2018; Westerholm et al., 2018).

2.2.4. Methanogenesis

Methanogenesis is the last phase of AD, which is carried out by methanogenic archaea. Methanogens have unique properties such as H_2 oxidation, CO_2 reduction, and utilisation. Furthermore, in the absence of O_2, methanogenic bacteria employ H_2 and CO_2 as substrates together with formate, methanol, and acetate to generate methane (Wagner, Watanabe, & Shima, 2018; Lyu, Shao, Akinyemi, & Biology, 2018). Methanogens are slow-growing microbes that are totally anaerobic (very sensitive to O_2) and can only digest a limited number of organic substances for carbon and energy (Lyu et al., 2018). Researchers have discovered 65 different species of methanogens, which are classified into five orders: methanobacteriales, methanococcales, methanomicrobiales, methanosarcinales, and methanopyrales (Wang, Shen et al., 2018; Wang, Wang et al., 2018; Wang, Hawkins et al., 2018).

Furthermore, they are further classified into three classes based on substrate utilisation, which are as follows: (a) methylotrophic methanogens—methanogens that use methyl and other single carbon compounds; (b) hydrogenotrophic methanogens—methanogens that use CO_2 and H_2 as carbon and energy sources and convert them to methane; and (c) acetoclastic methanogens—methanogens that convert acetate into methane. Among others, acetoclastic methanogens, such as the genus Methanosaeta, are responsible for most of the generation of methane and have a higher relative abundance (Gomez Camacho & Ruggeri, 2018; Peng, Chang et al., 2018; Peng, Zhang et al., 2018).

Another acetoclastic methanogen genus, Methanosarcina, has versatile metabolic pathways and is relatively tolerant to stresses (e.g., low pH and high VFAs) (Centler et al., 2018; Peces, Astals, Jensen, & Clarke, 2018; Peng, Chang et al., 2018; Peng, Zhang et al., 2018; Tian et al., 2018). Hydrogenotrophic methanogens, on the other hand, are less abundant in AD than acetoclastic methanogens. Furthermore, hydrogenotrophic methanogens are more resistant to hostile environments than acetoclastic methanogens. Under normal circumstances, there is a significant population change in the methanogenic community from acetoclastic to hydrogenotrophic (Guermazi-Toumi, Chouari, & Sghir, 2018; Kadier et al., 2018; Ziels et al., 2018).

2.3. Classification of the AD process

There are three types of AD based on the total solids (TS) content of the substrate: low-solids or "wet" digestion for TS less than 20%, semi-dry digestion for TS around 20%, and high-solids or "dry" digestion for TS greater than 20% (Shahriari et al. 2011). Compared to wet digestion, dry digestion offers many benefits, including reduced water use, lower digestate slurry production, more concentrated nutrients, improved transportation efficiency, and more efficient use of digesters (Zhou et al. 2019). This kind of AD has a number of drawbacks, including difficulties in obtaining appropriate bacterial contacts and decreased performance (Shahriari et al. 2011).

The substrate is first adjusted to a specified TS content before being fed into the digestion system for wet digestion, and process water may be required for dilution, which can also dilute inhibitory chemicals (Li 2015). In general, water addition is only required when the water content of the feed materials is insufficient, because cow manure slurry frequently contains enough water (generally TS content around 10%, Seadi et al. 2008) for digestion. Wet digestion is often carried out in continuously stirred tank reactors (CSTR) or wet single-pass digesters, where the feedstock can be appropriately mixed using existing mechanical, hydraulic, or pneumatic mixing equipment (Li 2015).

2.4. Factors Influencing Anaerobic Process

Different biotic and abiotic variables impact AD performance and long-term stability. The production of the main product of the process, biogas, depends on both the operational parameters (such as temperature, pH, retention time, C/N ratio, organic loading rate, substrate composition, optimal amount of essential nutrient, trace elements) and the diversity and activity of different microbial communities involved in different stages of the AD process. The following are some of these fundamental elements.

2.4.1. Temperature

Temperature is the most critical component that controls the AD process since different methanogens are temperature sensitive. Even minor changes in AD operating temperature can affect biological activities, such as the inhibition of some anaerobic bacteria, particularly methane-forming bacteria (Liu et al., 2018). The AD process has been run at various temperatures, but an optimal temperature is required for steady and effective fermentation. In general, three types of AD processes have been developed based on temperature ranges: psychrophilic AD (10-20°C), mesophilic AD (30-40°C), and thermophilic AD (50-60°C) (Hupfauf et al., 2018; Liu et al., 2018).

Mesophilic AD and thermophilic AD are two typical biogas generation techniques; the choice of each depends on a variety of criteria. Because of the high working temperature, thermophilic AD sacrifices various benefits, including high metabolic rates, high biogas production, and pathogen inactivation. Temperatures between 40 and 50°C, on the other hand, restrict the activity of bacteria that form methane. Mesophilic AD, on the other hand, may maintain high organic loading rates while having a reduced metabolic rate. Most methanogenic microorganisms are mesophilic, with only a few exceptions being thermophilic; this is due to thermophilic methanogens being more susceptible to rapid heat changes than mesophilic methanogens (Wang et al., 2018).

Temperature variations have an impact on the relative abundance and variety of AD communities. Higher temperatures put the community under selection pressure, resulting in the enrichment of resistant strains and a loss of diversity (Wang et al., 2018). Therefore, mesophilic AD has a more diverse archaeal community than the thermophilic AD process (Kim et al. 2018; Liu et al. 2018).

2.4.2. Retention time

HRT is a critical parameter that should be maintained for an optimum amount of time in order to eradicate dead zones and promote effective syntrophy for the creation of active microorganisms. Because the metabolic activity and development of anaerobic microorganisms are often sluggish, it is recommended that the retention period be twice as long as the creation time of slow growing methanogens for stable AD operation. The optimal value of HRT varies from one process to another depending on the quality and composition of the feedstock, the temperature of the process, the technology of the process and the type of digester (Kadier et al., 2018; Guermazi-Toumi et al., 2018; Ziels et al., 2018).

However, to prevent the reactor from being cleaned out, it is important to offer 10-15 days of HRT to keep and return their biomass. Hydrolytic and acid-forming bacteria, on the other hand, regenerate faster and are less likely to wash out of the digester. The slower rate of methanogen development is also responsible for the longer starting period of a biogas plant, which can last up to three months. This is also one of the reasons why the amount of inoculating sludge needed to start the plant at full capacity is generally not available immediately after feeding. On the contrary, a shorter retention time is significantly helpful in overcoming the cost of a biogas plant due to a reduction in digester volume, even if you sacrifice the quantity and quality of biogas products (Tan et al. 2018; Tang et al. 2018).

The increased HRT in anaerobic digestion seems to result in a greater elimination of volatile solids, resulting in a larger biogas output. However, an optimal period of HRT is still required for AD stability. For example, increasing retention duration beyond 12 days has little effect on volatile solid digestion, as biogas production remains high in the early stages but progressively decreases as the process progresses (Tabatabaei et al. 2018). Higher HRT during AD also increases volatile mass removal capacity, required digester volume, and buffering capacity for protection against shock loadings and toxic compounds in reactor wastewater and sludge (Buffière et al., 2018).

2.4.3. pH

The pH of the process also has a considerable impact on the effectiveness of anaerobic digestion, making it a fundamental parameter for the development of various microorganisms at various stages (Wang et al., 2018). In a two-stage AD, adjusting higher pH in the second stage is more important than in the first. Methanosarcina is the only methanogen genus that can handle pH 6.5 and below, whereas all other methanogenic bacteria's metabolism stops at pH 6.7. In AD, natural processes have developed to keep the pH in the neutral region, which is generally maintained by a natural buffering operation in the digester. CO_2 is continually emitted and escapes into the atmosphere, but as the pH drops, CO_2 dissolves in the substrate and remains in the form of neutral molecules. However, when the pH rises, the dissolved carbon converts to carbonic acid and vice versa (Sträuber et al. 2018).

2.4.4. Substrate composition

The content and degradability of the feedstock used as a substrate have a direct impact on the production of biogas in AD. Biogas production uses almost all substrates that comprise carbohydrates, proteins, and lipids as the main components. Cow and pig manure, municipal sewage sludge, food waste, fruit/vegetable waste, paper, and pulp are the feedstocks that are used the most frequently for biogas generation. Food and vegetable waste create more methane than cowdung and sludge, for example (Maragkaki et al., 2018; Okonkwo et al., 2018; Valenti et al., 2018). Carbohydrates, proteins, and cellulose are clearly the key components in most substrates, which account for the bulk of biogas generation.

In anaerobic co-digestion, Vivekanand et al. (2018) discovered a synergistic impact of diverse substrate compositions. Using the biomethane potential test (BMP), three different substrates were tested, namely manure, fish ensilage and whey, for biogas generation. The cumulative methane yields for cellulose (control), whey, manure, and fish ensilage digested as mono-substrates were 363, 274, 180, and 740 ml/gVS, respectively, while the degree of biodegradation was highest for fish ensilage up to 99% and lowest for manure 28%, according to the results of this study. In this study, the synergistic impact of several substrate combinations was also investigated, with all mixing ratios (85:15; 75:15; 50:50; 25:75; 15:85) of substrate whey and manure showing no synergistic effect on methane output. Furthermore, the deterioration rate reduced as the manure ratio increased.

Co-digestion of whey and fish ensilage at an 85:15 ratio also enhanced biogas generation by 13%. However, at higher fish ensilage concentrations (15%-85%), co-digestion with whey biodegradation fell from 91% to 83%, indicating that only lower fish ensilage concentrations resulted in co-digestion synergisms. On the contrary, a synergistic 84% increase in biogas occurred in an 85:15 substrate ratio of manure and fish ensilage, while biodegradation varied between 79% and 109% during co-digestion of manure and fish ensilage. Furthermore, it was established that in co-digestion, substrate composition, and biodegradability enhanced the methane output from each feedstock handled in mono-digestion in a few situations.

2.4.5. Organic loading rate

The quantity of volatile solid (VS) of organic materials put into the digester every day is referred to as the organic loading rate. Volatile solids (VS) generally contribute to the degradable fraction of solid organic matter, but the non-degradable portion, which includes certain non-digestible volatile solids, is known as a "fixed" solid. Although increased OLR leads to higher biogas generation, a longer retention period is necessary for the full conversion and digestion of organic waste by microorganisms. Furthermore, feeding too much volatile material into the digester increases the generation and accumulation of volatile acid, which affects the pH and alkalinity of the digester. The exact loading rate depends on the reactor design, biomass degradability, and microbiological activity. Furthermore, the most significant parameters to achieve maximum OLR include mass transfer between incoming waste and biomass, temperature, pH, toxicity level, and staging and design of phased digesters (Azzahrani et al. 2018; Musa et al. 2018).

A total solid concentration of 8.0%-10.0% is typically desired for the functioning of an AD reactor with any feedstock. In the case of dairy manure, a total solid concentration of 15.2% yields the maximum biogas output; moreover, for fresh dairy manure, a total solid concentration of 13.0% to 15.0% seems to be most suitable. Several research on the influence of OLR on the AD process have been published. Morken et al. (2018) investigated the performance and kinetics of dairy cow slurry (DCS) and municipal food waste (MFW) co-digestion at increasing OLR. For co-digestion, four distinct reactors were run with constant DCS and varying MFW concentrations, namely 0%, 14.0%, 24.5%, and 32.2% (w/w). In this experiment, the specific methane generated was 110% higher in the reactor with the highest OLR compared to the reactor with the lowest OLR. Furthermore, increasing the OLR from 1.83 to 5.04 g VS L1 day1 resulted in 477% greater methane production per unit volume of the reactor. In the meanwhile, the HRT was cut from 25.3 to 17.2 days.

In summary, the connection between the kinetic constant and the OLR was discovered to be linear; hence, it was projected that as the OLR increased, so would the process's efficiency.

2.4.6. The C/N Ratio

A correct feedstock composition in terms of carbon and nitrogen is required for an effective AD process with a balanced C/N ratio. Carbon and nitrogen are both required for the development of anaerobic bacteria. Carbon serves as an energy source, but nitrogen is required for protein synthesis and the formation of cell structures. Microorganisms eat carbon 25-30 times quicker than nitrogen during AD. To achieve this need, microorganisms require a C to N ratio of 20-30:1, with the majority of the carbon being rapidly degradable. In AD, an appropriate C/N ratio is a critical metric. At greater C/N ratios, nitrogen will no longer react with leftover input carbon, resulting in sluggish gas generation. Similarly, with lower C/N, excess nitrogen accumulates in the form of ammonium ion (NH4+), resulting in an increase in the total ammonia nitrogen (TAN) of the digester and the pH. Higher concentrations of TAN and digester pH levels are harmful to methanogen activity and can result in the failure of the AD process (Braz et al., 2018).

Normally, multiple substrates with varied carbon and nitrogen compositions are combined for co-digestion in order to adjust the optimum C/N ratio. Changing the feedstock for AD causes the optimal C/N ratio to change. Several studies have shown the impact of the C/N ratio on the performance and productivity of the AD process. Betenbaugh et al. (2018), for example, investigated synergistic co-digestion of algal biomass and cellulose to optimise C/N ratio for increased biogas and methane output. During the experiment, the biomass of algal bacteria and plants (low C/N ratio) was codigested with cellulose (high C/N ratio); total production of methane increased as the C / N ratio of algal biomass increased from 5.7 to 20-30.

As a result, Ammar et al. (2018) investigated the role of C/N ratio in anaerobic co-digestion of municipal solid waste (MSW) and food waste (FW) at C/N ratios ranging from 20 to 40. According to the research, increasing the C/N ratio in response reduces biogas generation because of the lack of organic nitrogen for microbial development. However, the biogas generated from the co-digestion of all substrates was significantly greater than that produced from the mono-digestion control (MSW), indicating that the inclusion of FW as the co-substrate balanced the C/N ratio. Furthermore, for C/N ratio 20, the biogas and methane yields were 827 and 474.44 ml/gVS, respectively.

2.5. Utilization of the end products of biogas process

Biogas and processing residue (digestate) are always the end products of the biogas process. Biogas, which is made up mainly of energy-rich methane, can be used as a renewable energy source. On the other hand, the processing residue, which allows the recycling of organic matter and nutrients left over from the biogas process, can be used as is or further processed as an organic fertiliser product (Luostarinen 2013).

2.5.1. Utilisation of biogas

Biogas can be used for a variety of applications, including heat generation, combined heat and power generation (CPH), and refinement to transportation fuel or as gas supplied to the natural gas network (Motiva 2013). There are several elements of quality requirements for biogas use. Raw biogas is not suitable for current applications but can be burnt, which is why biogas facilities feature torch burners. Heating and energy generation do not need processing. It is sufficient to purify biogas to meet the needs of energy and heating equipment before use as combined heat and power (CHP) or biomethane (Kymäläinen & Pakarinen, 2015).

Heat utilisation

Heating is the easiest and most cost-effective method to use the generated biogas by burning it in a gas boiler to create hot water for heating or utilising it as an energy source in the kitchen (Motiva 2013). This may be accomplished using either a centralised or device-specific system. The heat of the centralised system is created in a boiler, from which it is transmitted to ultimate consumption through a medium, which is primarily water. The device-specific technology transmits biogas rather than heat, which is then burnt in the ultimate consumption facility (such as a gas-burning cooker, heater, stove, oven, and grill). A device-specific system may achieve up to 95% manufacturing efficiency (Kymäläinen & Pakarinen 2015). Because the procedure is straightforward, the boiler may be fully conventional. The boiler's burner must only be biogas compatible. Typically, only moisture is removed from biogas, for example, using a condensation tank for the heating boiler (Luostarinen 2013). Boilers primarily generate central heat, but they may also heat water, dry grain, and other items, as well as filter water. In summer, when heat demand is lower, energy output in farm-sized biogas facilities generally exceeds the farm's own heat energy requirement several times over. The farm biogas units have mainly turned to combined power and heat production (CHP system) (Motiva 2013).

Combined heat and power generation

In addition to heat generation, another typical way for using biogas is combined heat and power (CHP), in which a gas engine transforms a portion of the energy content of biogas into electricity and the remainder into heat. This is a cost-effective method to generate power and heat from a renewable energy source. A gas engine with a total efficiency of 80-90% produces around 30-40% electricity and the rest 60-70% heat (Makara et al. 2021). The most prevalent technological solution for burning biogas is to burn it in a gas-powered diesel engine or intake engine, which is becoming more popular (Motiva, 2013). The electricity generated by biogas can be used on the farm to power electrical equipment such as pumps, control systems, and mixers, with surplus electricity exported to the national grid (Al Seadiet al. 2008). Surplus heat from the CHP plant's engine, on the other hand, may be utilised to heat the biogas plant and, in certain cases, surrounding buildings. When heating the farm does not require a lot of thermal energy, the heat production capability may go unused, especially in the summer (Motiva 2013).

Biogas as vehicle fuel

Biogas may be utilised as transportation and machine fuel in a variety of methods, either unrefined or refined into methane vehicles. When biogas is refining into fuel using a separate cleaning apparatus, the gas is cleansed of hydrogen sulphide and particulates before being separated from the gas by carbon dioxide. The goal is to remove as much carbon dioxide as possible while refining transportation fuel since it reduces the calorific value of the gas. The purification process produces biomethane (methane content often more than 90%), which is the only fuel acceptable for all kinds of engines and modes of transportation. It, like natural gas, can be used as transport and machine fuel through a separate pressurisation and refuelling unit or through the natural gas network (Kymäläinen & Pakarinen 2015).

Agricultural tractors may be converted to solely operate on biomethane. However, when utilising biogas, it is a so-called Dual Fuel solution, in which the tractor runs on both light fuel oil and biogas (biomethane). The tractor uses gasoline automatically as the engine speed range varies. If half of the work was done with a biogas tractor and half of the fuel used was biogas, the needed quantity of gas in an area of around 500 hectares would be roughly 25,000 m^3. Although their usability is comparable to diesel tractors and their technology does not need as sophisticated development effort, the so-called Dual Fuel solution is not as ecologically benign as specifically made biogas vehicles (Kari & Häkkinen 2014).

2.5.2. Digestate utilization

In addition to biogas, the biogas process produces a nutrient-rich processing or digestion waste, which has value as a fertiliser and soil conditioner. The digestate comprises the original feed's nutrients as well as the leftover weakly degradable organic materials. The composition and nutritional value of the digestate vary depending on the raw material used, the type of biogas process used, and the duration of residence of the item in the digester (Kari &Häkkinen 2014). When manure decomposes throughout the biogas process, the majority of organic nitrogen in manure, which is attached to proteins, is changed or mineralised to ammonium nitrogen, which is simpler for plants to use. Depending on the feed material and the processing circumstances, around 20% or more of the total nitrogen in manure is transformed into ammonium nitrogen; in plant biomass, the percentage can range between 50 and 80%. Manure digestion reduces nitrogen leaching from farms, and well-decomposed digestion waste, which is nearly odourless, also reduces unpleasant odours of feed biomass (Horn et al., 2020).

The digestate composition varies depending on the biogas process. It might resemble sludge (wet digestion) or dry manure (dry digestion). Composting and separation are the most common ways to further process digestion leftovers. When digestion residue is separated via a screw, hopper or strainer belt to separate the liquid fraction, that is, reject water and the dry fraction, the transport and handling of pulp are simplified. The separation results in the majority of the soluble nitrogen ending up in the liquid fraction and the majority of the phosphorus ending up in the dry fraction. The dry portion may be stored and used later, or it can be put directly in the field. The dry fraction may also be post-ripened and composted by including additional organic material, yielding a humus-like compost as a final product. Additionally, rejects can be returned to the biogas process with sludge manure, further processed into nutritious products, or kept in a sludge tank for use in the field as is. Because of the large and readily volatile nitrogen content of the reject water, the residue should be soiled as soon as possible, unless it is disseminated by planting, so that the nitrogen does not escape and is efficiently utilised by the plants (Horn et al. 2020; Tiainen 2016).

2.6. Solid waste management in Nigeria

Due to population growth and industrialisation, the quantity and variety of waste in Nigeria is steadily increasing (Imam et al. 2008), while the basic solid waste management system based on collection, transportation and disposal remains highly inefficient and ineffective, particularly in urban areas (Ayotamuno & Gobo 2004). Nigeria is the most populated and tenth biggest nation in Africa, with a population of approximately 150 million people spread over 923,768 square kilometres (World Bank 2012).

2.6.1. Legal Framework

Nigeria has a three-tier government structure consisting of federal, state, and local governments, with different tasks assigned to each tier according to the constitution (Afon 2007). The landmark Federal law on environmental protection in Nigeria was Decree 58 of 1988, which created the Federal Environmental Protection Agency (FEPA) to address Nigeria's expanding waste management and pollution problems (Walling et al. 2004; Imam et al. 2008).

The local government is legally responsible for solid waste management, but the state government comes in to supplement their efforts, particularly in state capitals like as Kaduna, Lagos, and Port-Harcourt (Afon 2007). Despite their efforts, Nigeria's solid waste management plan is characterised by a system beset with lack of accountability and refuse-filled areas, sewers, and roadways (Dauda & Osita 2003; Walling et al. 2004).

2.6.2. Components of solid waste creation and management

Households responsible for 90% of urban garbage (Solomon et al. 2009). It contains a high organic content, which is similar with trash from developing nations such as Ghana, China, Jordan, and Palestine (Qdais 2007; Al Khatib et al. 2010; Zhao et al. 2009; Fobil et al. 2010). The nature of waste in Nigeria shows a recyclable component of more than 40%, with an estimated recycling rate of 8-22% carried out by the informal sector (Wilson et al. 2009). Open dumping, open burning, and composting are further choices (Dauda & Osita 2003; Imam et al. 2008; Ogwueleka 2009).

Temporarily, waste is held inside houses or at community disposal locations in different sizes of bins, bin bags, baskets, buckets, and directly on the ground at communal sites (Abdullahi et al. 2008). The state/local government collects co-mingled garbage in an irregular manner, using contractors and/or informal waste management (Imam et al. 2008). More than half of the population disposes of garbage in community sites, which are essentially open landfills (Dauda & Osita 2003). Lorries, tippers, loaders, trucks, tractors, push carts and wheel barrows are common modes of waste transportation (Imam et al. 2008). Collection and transportation account for 70-80% of overall waste management costs in Nigeria (UNDP 1998), with the government funding the majority of this. Irregular trash collection and transportation is due in part to vehicle breakdowns and insufficient facilities and equipment (Adewole 2009).

2.6.3. Attitude and awareness

Research reveals a generally negative attitude towards waste management (Imam et al. 2008; Adewole 2009). In addition to environmental management topics included in junior secondary school curricula, the local and state governments responsible for raising awareness on solid waste management issues frequently use seminars, conferences, workshops, and training sessions as the most common techniques in creating awareness observed during the survey (Uhuo & Zavodska 2010).

3. Methods

3.1. Research Design

The study employed a mixed research design approach to collect data from the target population. This mixed method will involve the application of quantitative and qualitative analysis to the data. Semi-structured questionnaire was used as the research instrument to obtain data from the target population. The biogas yield experiment was set up in a Completely Randomized Design (CRD) in the laboratory.

3.2. Study population

The population of this study consists of all cassava farmers and processors in Ilaro, Ogun State, Nigeria. It is important that all respondents have experience with cassava processing and basic knowledge of biogas production, either directly or indirectly.

3.3. Sample Size

To determine the sample size, the formula of Fisher et al. (1998) will be used to calculate the sample size needed.

$$n = \frac{Z^2 p(1-p)}{e^2}$$

Where n= the sample size, Z depends on the degree of confidence level, the degree of variability is denoted by P and expressed as decimal while e is the precision rate.

Confidence level = 85%, Z = 1.44, P = 26%, e=±5%

$$n = \frac{1.44^2 \times 0.25(1-0.25)}{0.05^2}$$

n = 296

A total of 300 sample will be used for this research work.

3.4. Lab work

3.4.1. Collection of Raw Materials

Fresh cassava, weighing 5 kg, was procured from Ilaro, Ogun State, Nigeria, for biogas production, then washed, blended, strained, and refrigerated at approximately 4 ℃; the chicken inoculum used in the experiment was sourced from Agricultural biogas plant in Citov (Czech Republic).

3.4.2. Experimental Design

The experimental setup was conducted in an anaerobic digester. The digester is made up of fermenter where the organic material biodegrades to produce biogas and water displacement where the volume of biogas produced is collected and measured.

Fermenter: This chamber contains the organic material (substrate) that is being broken down by microbes. The fermenter also contains inoculum which is a mixture of microbes that jumpstart the fermentation process.

Water displacement chamber: This chamber collects the biogas produced in the fermenter. As biogas accumulates in this chamber, it displaces the water. The volume of displaced water correlates to the volume of biogas produced.

Connection tube: This tube connects the fermenter chamber to the water displacement chamber. It allows the biogas produced in the fermenter to flow into the water displacement chamber.

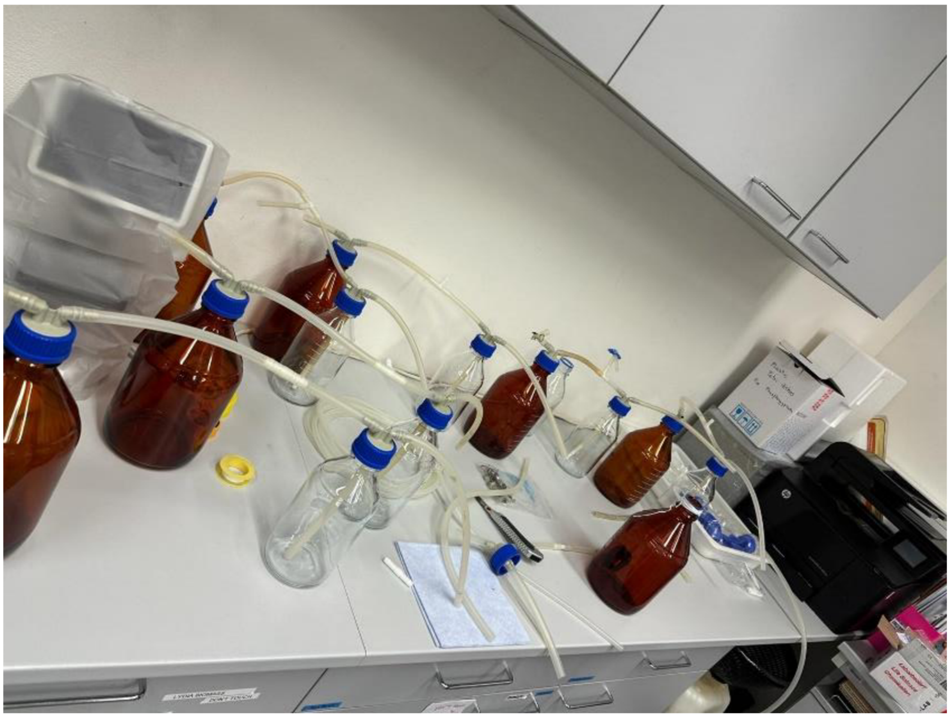

Figure 3.1: Digester setup

3.4.3. Processing of Cassava

The collected cassava underwent thorough washing, chopping into pieces, and grinding using a blender, followed by drying for Total Solid (TS) determination and incineration of a portion to determine Volatile Solid (VS) content.

3.4.4. Total Solids (TS) Determination

The following procedure was used to determine the total solids content of the substrate. First, a clean evaporating dish was heated in an oven at 103-105°C. It was then stored in a desiccator to cool and its weight was accurately recorded. A representative sample of the well-mixed substrate, with a volume that would result in a dried residue between 2.5mg and 200mg, was carefully measured. This sample was then transferred to the pre-weighed dish. The liquid in the dish was then evaporated completely in an oven set at 103-105°C. Once dry, the dish was allowed to cool completely in a desiccator to prevent moisture absorption. Finally, the weight of the dish with the dried residue was measured and the total solids content was calculated as a percentage of the original sample volume. This method determined the total content of solid material in the substrate, which included both organic and inorganic components.

3.4.5. Volatile Solids (VS) Determination

Volatile solids represent the portion of total solids lost as gas during combustion, primarily consisting of organic matter. After determining the TS content, the crucible containing the dried sample was transferred into a preheated muffle furnace (550°C ± 25°C) and combusted for 2 hours until all organic matter was oxidized; post-combustion, the crucible was cooled in a desiccator, and the weight of the crucible containing the ash residue (W3) was recorded.

3.4.6. Preparation of Chicken Inoculum

The chicken inoculum was obtained and sieved using a 1 mm sieve, then mixed homogeneously.

3.4.7. Experimental Set-up

Eight experimental configurations were established for the parametric study, with each configuration comprising three bottles connected in series; a biodigester cap, featuring a 2 cm diameter, was meticulously drilled, and a 46 cm plastic tubing was inserted into each bottle. Daily pH measurement was conducted using pH and Oxygen Redox Potential Meter, while the produced biogas composition was measured using Geotech BIOGAS 5000. Samples were cooled in a desiccator, and their net weight was recorded until a constant value was achieved.

3.4.8. Parameter Variation:

The experiment comprised four treatments, including a blank group, each representing different ratios of inoculum to cassava organic dry matter substrate. The treatments were as follows:

Treatment 1: Inoculum and Cassava organic dry matter substrate ratio of 1:2

Treatment 2: Inoculum and Cassava organic dry matter substrate ratio of 2:2

Treatment 3: Inoculum and Cassava organic dry matter substrate ratio of 4:1

Blank: Inoculum without cassava organic dry matter substrate

All trials were terminated when the daily methane output is less than 1% of the total methane production. The experiment was replicated twice under controlled laboratory conditions to minimize external variability. The selection of these ratios aimed to investigate the effects of varying inoculum to substrate ratios on biogas production efficiency and microbial activity in anaerobic digestion processes, with the blank treatment serving as a baseline for comparison.

3.5. Data Analysis and Presentation

Descriptive statistics, such as frequency distribution, means and percentages were used to describe the socio-economic characteristics of the respondents, examine the current practices and challenges in the management of cassava waste, and investigate small-scale production of biogas as a tool for rural development. However, the Likert scale was used to identify the awareness and knowledge of farmers, processors and other stakeholders regarding the potential of cassava waste for biogas production and the attitudes and perceptions of farmers and processors toward the adoption of cassava waste biogas production. Additionally, for easy analysis and computation, all statistical computations were done using Microsoft Excel and Statistical Package for Social Sciences (SPSS) version 26.

4. Results

4.1. Socioeconomic characteristics

The socio-economic characteristics of the respondents is presented in Table 4.1. The survey of 300 respondents engaged in the cassava enterprise in Ilaro, Ogun State, Nigeria, reveals a nuanced and diverse demographic landscape. In terms of gender, the data indicates a balanced participation with 53.7% being male and 46.3% female, emphasizing an inclusive involvement of both genders in the cassava sector. The age distribution showcases a dominant presence of individuals in their prime working years (25-34) at 59.3%, supplemented by significant representation from the younger demographic (18-24) at 15.7%. This suggests a workforce that combines experienced professionals with the fresh perspectives of youth. Marital status portrays a predominantly married workforce (69.3%), highlighting the family-centric nature of the cassava enterprise, while the presence of divorced (9.0%) and widowed (4.3%) individuals indicates a diverse range of life experiences within the community.

Educationally, the workforce is diverse, ranging from respondents with no formal education (9.7%) to those with tertiary education (43.0%). This variety underscores the importance of both practical skills and academic knowledge in the cassava enterprise. Household size diversification, with 46.3% falling within 3-4 members, suggests that the cassava sector supports families of various sizes, impacting the economic well-being of the community. The enterprise type distribution showcases engagement in cassava farming (42.3%), processing (45.0%), and both (12.7%), revealing a multifaceted approach to the cassava value chain, promoting resilience and sustainability.

Years of experience further emphasize the stability and maturity of the workforce, with 64.0% having 6-10 years of experience and 20.7% possessing more than 10 years. This seasoned workforce contributes to the industry's development and growth. The income distribution highlights the financial aspect of the cassava enterprise, with 54.3% earning more than ₦150,000 monthly. However, the presence of 2.0% earning less than ₦50,000 underscores potential income disparities, indicating a need for targeted interventions.

Table 4.1: Socio-economic characteristics of respondents

Characteristics	Frequency	Percent
Gender		
Male	161	53.7
Female	139	46.3
Age		
18 - 24	47	15.7
25 - 34	178	59.3
35 - 44	48	16.0
45 and above	27	9.0
Marital Status		
Single	52	17.3
Married	208	69.3
Divorced	27	9.0
Widowed	13	4.3
Educational level		
No formal education	29	9.7
Primary	38	12.7
Secondary	43	14.3
Vocational training	61	20.3
Tertiary	129	43.0
Household size		
1 - 2	38	12.7
3 - 4	139	46.3
5 - 6	55	18.3
More than 6	68	22.7
Enterprise type		
Cassava farming	127	42.3
Cassava processing	135	45.0
Both	38	12.7
Years of experience		
Less than 5 years	46	15.3
6 - 10 years	192	64.0
More than 10 years	62	20.7
Average monthly family income		
Less than ₦50,000	6	2.0
₦51,000-₦100,000	29	9.7
₦101,000-₦150,000	102	34.0
More than ₦150,000	163	54.3
Total	**300**	**100.0**

Source: Field survey, 2023

4.2. Current practices and challenges in the management of cassava waste

4.2.1. Current cassava waste mangement method

The result of current cassava waste management methods among 300 respondents in Ilaro, Ogun State, Nigeria presented in Figure 4.1 provides valuable insights into the practices employed by individuals within the cassava enterprise. The findings reveal a diverse range of approaches, each with its implications for both economic viability and environmental sustainability.

A significant proportion (47.3%) of respondents resort to burning as the primary waste management method. While burning may offer a quick solution, it raises environmental concerns, such as air pollution and the potential loss of valuable nutrients present in cassava waste. This calls for attention to more sustainable alternatives that balance the immediate disposal needs with long-term environmental health.

On the contrary, approximately 14.7% of the respondents engage in selling cassava waste, which presents a potential economic avenue within the waste stream. This emphasises the entrepreneurial opportunities that can arise from the by-products of cassava-related activities. Encouragement of such economic utilisation could not only provide financial benefits to individuals, but could also contribute to the overall economic development of the community.

The use of cassava waste as animal feed, both dried (9.3%) and wet (11.3%), reflects an understanding of the agricultural value of waste. This practice aligns with sustainability goals, offering a dual benefit of recycling waste and supporting local livestock farming practices. It suggests an awareness among some respondents of the potential ecological benefits of utilizing cassava waste in agricultural activities.

However, the data also highlights a segment of respondents (17.3%) who discard cassava waste, signalling a potential gap in knowledge or awareness regarding more sustainable waste management practices. This calls for targeted education and awareness programs to promote eco-friendly alternatives and foster a more responsible approach to waste disposal within the cassava industry.

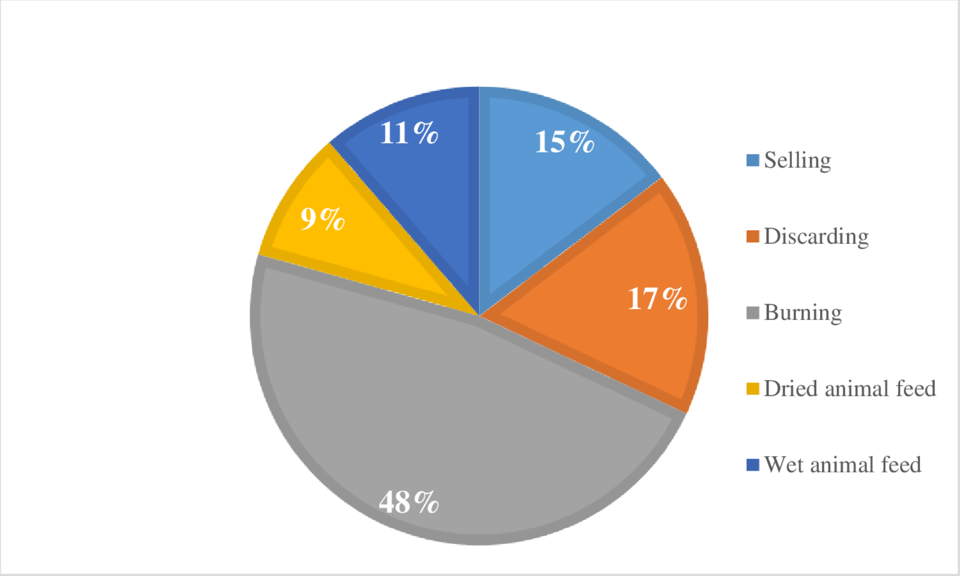

Figure 4.1: Current cassava waste management method of respondents

Source: Field survey, 2023

4.2.2. Challenges in the management of cassava wastes

The challenges in the management of cassava wastes as reported by respondents in Ilaro, Ogun State, Nigeria presented in Table 4.2 reflects the perceived difficulties encountered within the cassava enterprise. The challenges are presented in terms of both frequency distribution and percentages, providing a comprehensive understanding of the respondents' perspectives.

A notable challenge reported by respondents is the high cost of labor, with 16% strongly agreeing and 64.3% agreeing. This indicates a prevalent concern among a substantial majority regarding the economic implications of labor expenses in cassava waste management. The issue of low market demand for cassava waste products is widely acknowledged, with a substantial 68.3% strongly agreeing and 23% agreeing. This reflects a significant consensus among respondents about the limited market opportunities for cassava waste products, which could impact the economic viability of waste utilisation.

Respondents also strongly agree (67.3%) on the shortage of waste-disposing pits in the processing area, indicating a shared perception that infrastructure for proper waste disposal is inadequate. This highlights an infrastructural challenge that may hinder effective waste management practices. The challenge of inadequate water for washing away effluents is acknowledged by 60% of respondents, emphasizing the environmental considerations and resource limitations faced in the process of cassava waste management.

Furthermore, a majority of respondents (69.7%) strongly agrees on the challenge of inadequate knowledge and limited access to extension agents. This indicates a significant awareness among respondents of the need for education and support to improve cassava waste management practices. Regarding weather-related challenges, 19.7% strongly agree and 36.7% agree that seasonal or inadequate sunshine poses difficulties for sun-drying cassava waste. This indicates that weather conditions are perceived as a challenge by a considerable proportion of respondents, potentially affecting the feasibility of certain waste management practices. The majority of respondents (70.7%) strongly agrees that the long value addition process is a significant challenge. This highlights the perceived time constraints and complexities involved in adding value to cassava waste, which could affect the efficiency of the waste utilisation process.

Table 4.2: Challenges in management of cassava wastes

Challenges in management of cassava wastes	Strongly Agree F(%)	Agree F(%)	Uncertain F(%)	Disagree F(%)	Strongly Disagree F(%)
High cost of labour	48(16)	193(64.3)	36(12)	17(5.7)	6(2)
Low market demand for cassava waste products generated	205(68.3)	69(23)	13(4.3)	13(4.3)	-
Shortage of waste disposing pits in the processing area	202(67.3)	97(32.3)	1(0.3)	-	-
Inadequate water to wash away effluents	180(60)	106(35.3)	11(3.7)	1(0.3)	2(0.7)
Inadequate knowledge and access to Extension agents	209(69.7)	88(29.3)	3(1.0)	-	-
Seasonal/inadequate sunshine for sun-drying of cassava waste	59(19.7)	110(36.7)	52(17.3)	47(15.7)	32(10.7)
Long value addition process	212(70.7)	59(19.7)	11(3.7)	13(4.3)	5(1.7)

Source: Field survey, 2023

4.3. Awareness regarding the potential of cassava waste for biogas production

4.3.1. Awareness about improved forms of utilizing cassava wastes

The result on awareness about improved forms of utilizing cassava wastes in Ilaro, Ogun State, Nigeria presented in Figure 4.2, reveals encouraging trends in the community's knowledge of advanced cassava waste management practices. A substantial majority of respondents, comprising 77.3%, express awareness of improved methods. This high percentage suggests that a significant portion of the surveyed population is informed about and knowledgeable regarding innovative approaches to cassava waste utilization.

On the other hand, 22.7% of the respondents indicate a lack of awareness about improved forms of cassava waste utilisation. Although this represents a smaller segment, it suggests that there is still work to be done to reach certain portions of the community with information on advanced cassava waste management methods. Bridging this awareness gap is essential for ensuring a comprehensive understanding of sustainable practices and promoting their adoption throughout the community.

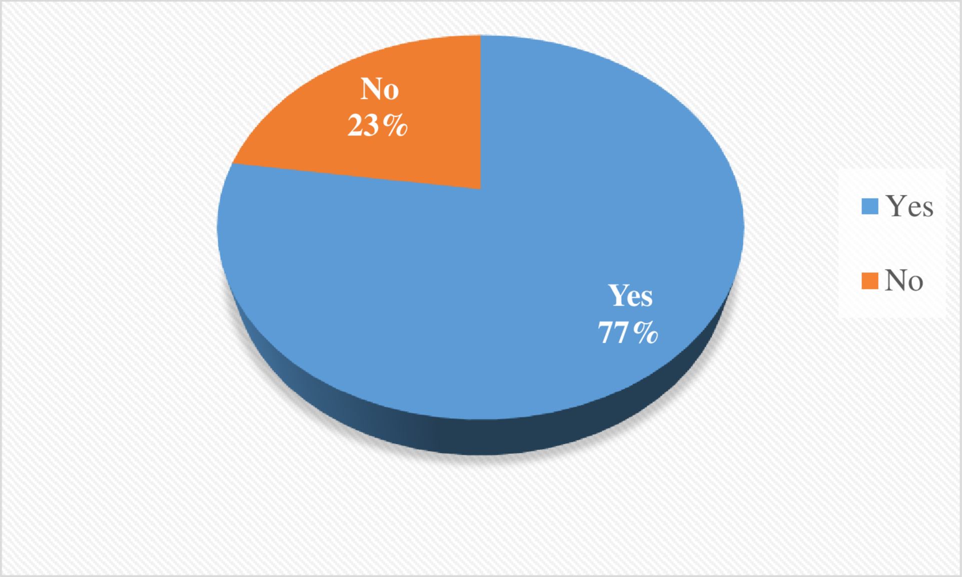

Figure 4.2: Awareness about improved forms of utilizing cassava wastes

Source: Field survey, 2023

4.3.2. Cassava waste utilization forms

The result of the cassava waste utilisation forms in Ilaro, Ogun State, Nigeria, presented in Figure 4.3, paints a picture of a community actively engaged in diverse and sustainable approaches to the management of cassava waste. The predominant form of utilization is as animal feed, with a substantial 55.0% of respondents adopting this method. This underscores the dual benefits of waste management and the production of a valuable resource for livestock farming, aligning with principles of sustainable agriculture. A noteworthy finding is the diversity in cassava waste utilization methods reported by respondents. Mushroom production, adopted by 10.0%, stands out as a form that not only contributes to waste management, but also has the potential for the addition of economic value through the sale of mushrooms. Additionally, the use of cassava waste for biogas production (10.7%) and ethanol production (7.7%) reflects an environmentally conscious approach, converting organic waste into renewable energy sources. The utilization of cassava waste for fertilizer production, reported by 16.7% of respondents, emphasizes a commitment to enhancing agricultural productivity through sustainable practices. This method contributes to soil fertility and aligns with broader goals of promoting eco-friendly and nutrient-rich farming practices.

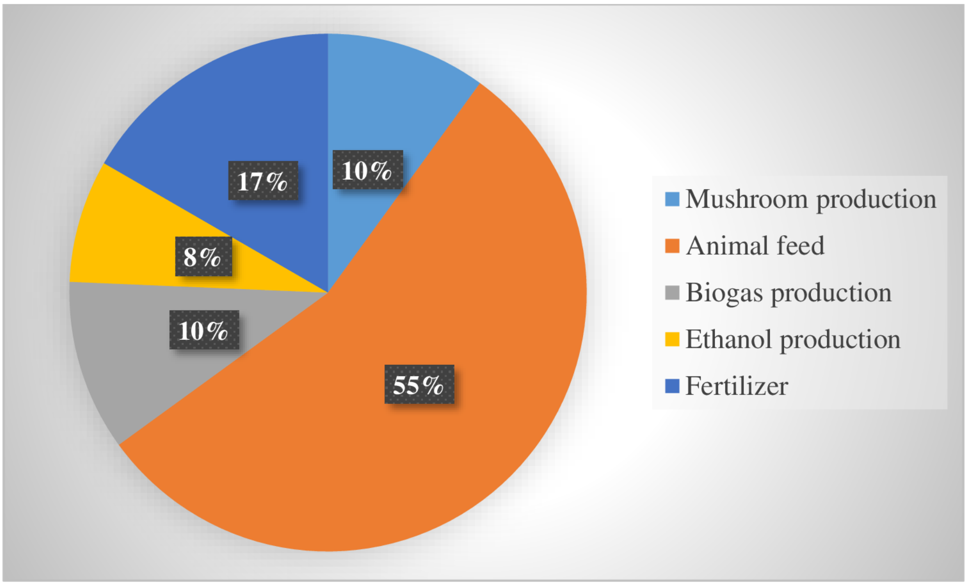

Figure 4.3: Cassava waste utilization forms

Source: Field survey, 2023

4.3.3. Willingness to adopt biogas

The result on the willingness to adopt biogas technology in Ilaro, Ogun State, Nigeria presented in Figure 4.4, signifies a positive and encouraging trend within the community. A substantial majority, comprising 80.0% of respondents, express a strong willingness to adopt biogas technology. This overwhelming support suggests a proactive and environmentally conscious community that is open to embracing sustainable energy solutions. The high percentage of respondents willing to adopt biogas technology reflects a shared commitment to reducing environmental impact and contributing to a more sustainable and eco-friendly energy landscape. However, it should be noted that 20.0% of the respondents indicated a reluctance or lack of willingness to adopt biogas technology.

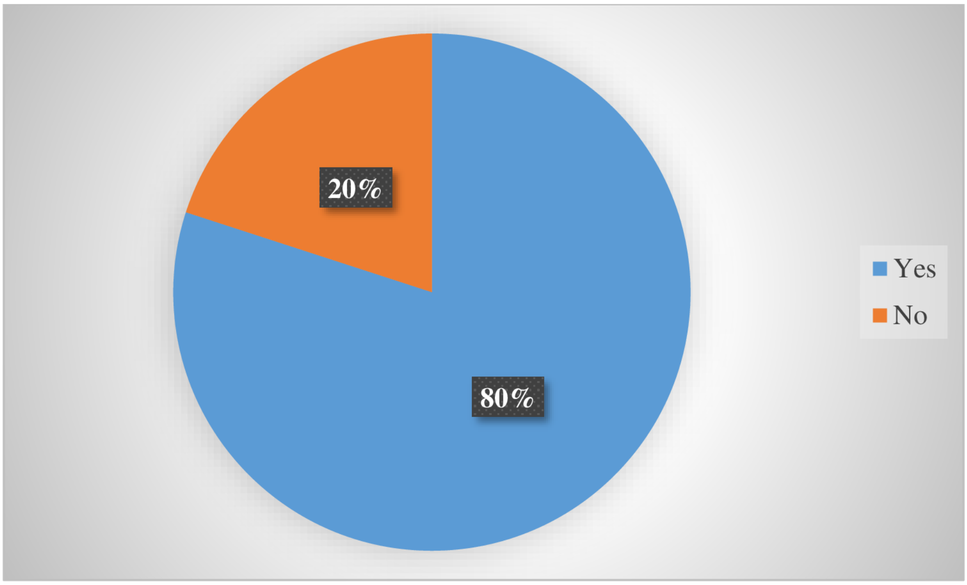

Figure 4.4: Willingness to adopt biogas technology

Source: Field survey, 2023

4.4. Perceptions of cassava stakeholders on adoption of biogas

The result on the perceptions of cassava stakeholders regarding the adoption of biogas technology in Ilaro, Ogun State, Nigeria presented in Table 4.3, reveals a highly positive and encouraging outlook within the community. Across various statements, stakeholders express favourable perceptions of the potential benefits associated with biogas adoption. A substantial percentage, 80.0%, agrees strongly or agrees that the adoption of biogas technology improves energy security. This reflects a community that recognises the role of biogas in ensuring a reliable and sustainable energy supply, highlighting a positive response to the potential impact of technology on energy availability.

In addition, more than half of the stakeholders, 54.7%, strongly agree that biogas adoption brings environmental benefits, and an additional 43.0% agree with the statement. This robust acknowledgment of the environmental advantages underscores a heightened awareness and commitment to sustainability within the community. The recognition of biogas as an additional source of income is evenly split, with 51.0% strongly agreeing and 48.7% agreeing. This suggests that stakeholders perceive economic opportunities associated with biogas adoption, contributing to income generation and potentially enhancing the overall economic well-being of the community.

The majority of stakeholders strongly agree (57.0%) or agree (36.7%) that biogas adoption leads to reduced energy costs through self-provision, such as hot water generation. This positive perception aligns with the economic benefits tied to self-sufficiency in energy provision. The strongest consensus emerges in the area of proper management of cassava wastes, with a significant 75.0% of stakeholders strongly agreeing and an additional 21.7% agreeing. This overwhelming support underscores a shared belief that biogas adoption contributes significantly to waste management, reducing pollution and contamination risks. Efficiency gains are also recognized, with 57.3% of stakeholders strongly agreeing that biogas adoption reduces the workload for cassava waste handling. Another 39.0% agree, indicating a widespread perception that biogas technology streamlines and eases the processes associated with cassava waste management.

Table 4.3: Perceptions of cassava stakeholders on adoption of biogas

Perceptions of cassava stakeholders on adoption of biogas	Strongly Agree F(%)	Agree F(%)	Uncertain F(%)	Disagree F(%)	Strongly Disagree F(%)
Improved energy security	126(42)	149(49.7)	14(4.7)	8(2.7)	3(1.0)
Environmental benefits	164(54.7)	129(43.0)	2(0.7)	4(1.3)	1(0.3)
Additional source of income	153(51.0)	146(48.7)	-	1(0.3)	-
Reduced energy costs through self-provision (e.g., hot water)	171(57.0)	110(36.7)	18(6.0)	1(0.3)	-
Proper management of cassava wastes(reduced pollution/ contamination risk)	225(75.0)	65(21.7)	9(3.0)	1(0.3)	-
Reduced workload for cassava wastes handling	172(57.3)	117(39.0)	9(3.0)	1(0.3)	1(0.3)

Source: Field survey, 2023

4.5. Potential barriers and constraints to utilizing cassava waste as a feedstock for biogas production

The result on potential barriers and constraints to utilizing cassava waste as a feedstock for biogas production in Ilaro, Ogun State, Nigeria presented in Table 4.4, reveals several challenges that may hinder the widespread adoption of biogas technology within the community.

A predominant concern among stakeholders is the perceived financial burden associated with high investment and running costs, as indicated by a significant 88.7% strongly agreeing with this statement. This suggests that the economic feasibility of implementing biogas systems is an important consideration, which highlights the need for financial incentives or support mechanisms to alleviate this barrier and encourage adoption. Uncertainty regarding economic benefits is another notable barrier, with nearly half of respondents strongly agreeing and an additional 48.7% agreeing. This indicates a level of scepticism or lack of clarity among stakeholders about the potential returns on investment from the use of cassava waste for biogas production. Addressing this uncertainty through awareness campaigns and economic analyses may help build confidence among potential adopters.

The lack of information about biogas systems and a corresponding lack of technical know-how emerge as significant barriers, with 79.3% strongly agreeing on the former and 66.0% strongly agreeing on the latter. These findings underscore the importance of comprehensive awareness programs and capacity-building initiatives to provide stakeholders with the knowledge and skills necessary for successful biogas adoption. The perception of insufficient government support as a barrier, expressed by 60.0% strongly agreeing, further emphasizes the need for a supportive policy environment and government initiatives to facilitate the adoption of biogas technology. Policymakers could play a crucial role in addressing this constraint by implementing measures that incentivize and promote the adoption of sustainable technologies.

Table 4.4: Potential barriers and constraints to utilizing cassava waste as a feedstock for biogas production

Potential barriers to utilizing cassava waste as a feedstock for biogas production	Strongly Agree F(%)	Agree F(%)	Uncertain F(%)	Disagree F(%)	Strongly Disagree F(%)
High investment and running (e.g., repair) costs	266(88.7)	28(9.3)	4(1.3)	1(0.3)	1(0.3)
Uncertain economic benefits	145(48.3)	146(48.7)	4(1.3)	3(1.0)	2(0.7)
Lack of information about biogas system	238(79.3)	61(20.3)	1(0.3)	-	-
Lack of technical know-how about biogas system	198(66.0)	101(33.7)	1(0.3)	-	-
Insufficient government support	180(60.0)	120(40.0)	-	-	-

Source: Field survey, 2023

4.6. Biogas yield of cassava waste and inoculum

4.6.1. Biogas volume (ml)

The result presented in figure 4.5 shows the gas volume (ml) and cumulative gas volume (ml) produced over a period of nine days in an experiment measuring the biogas yield from a mixture of inoculum + cassava (2:1). it is evident that there was a steady increase in biogas production over the course of the experiment. Initially, on day 1, there was a relatively low gas volume of 211.25 ml, which is expected at the beginning of the fermentation process. However, as the experiment progressed, there was a significant increase in gas production, reaching a peak volume of 1382 ml on day 2. This rapid increase suggests that the microbial activity responsible for biogas production was becoming more active and efficient as fermentation progressed.

Subsequently, there was a slight decline in gas production on days 3 and 4, possibly due to factors such as decrease in pH within the digester. However, the gas production rebounded on day 5, indicating that the microbial community adapted to the changes and continued to produce biogas efficiently. Towards the end of the experiment, there was a gradual decrease in gas production, with only minimal volumes recorded on days 8 and 9. This decline could be attributed to the depletion of available nutrients in the substrate or the accumulation of inhibitory by-products that may have affected microbial activity.

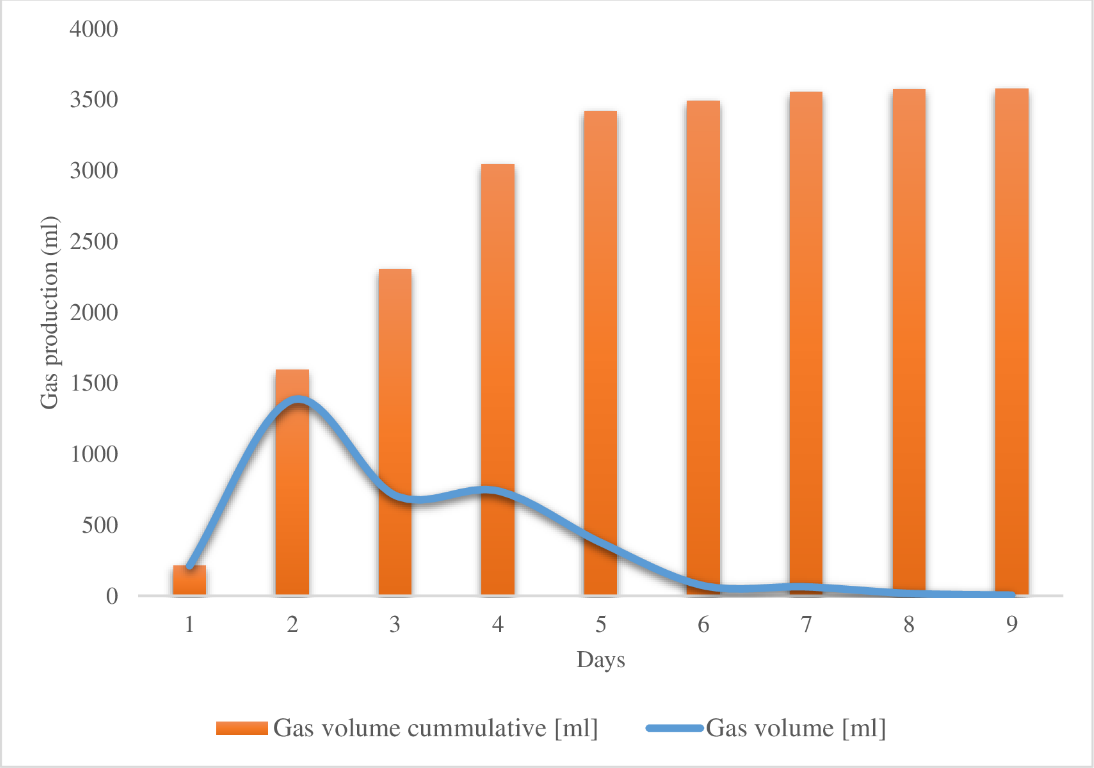

Figure 4.5: Biogas volume (ml) produced by inoculum 2: cassava waste 1

Source: Researcher's lab experiment (2024)

From the result presented in Figure 4.6, it is evident that there was a substantial increase in biogas production over the duration of the experiment using inoculum 2: cassava 2. The initial gas volume on day 1 was relatively high at 1236.5 ml, indicating that the fermentation process began with a significant amount of microbial activity. This early spike in gas production suggests that the inoculum and cassava (2:2) provided an ideal environment for the microbial community to thrive.

As the experiment progressed, there was a steady increase in cumulative gas volume, with notable peaks on days 2, 7, and 8. These peaks likely correspond to periods of heightened microbial activity, possibly fuelled by the availability of nutrients in the substrate or favourable environmental conditions within the digester. The overall trend of increasing gas production continued until day 10, after which there was a gradual decline in gas volume. This decline could be attributed to factors such as substrate depletion or the accumulation of inhibitory by-products that may have hindered microbial activity.

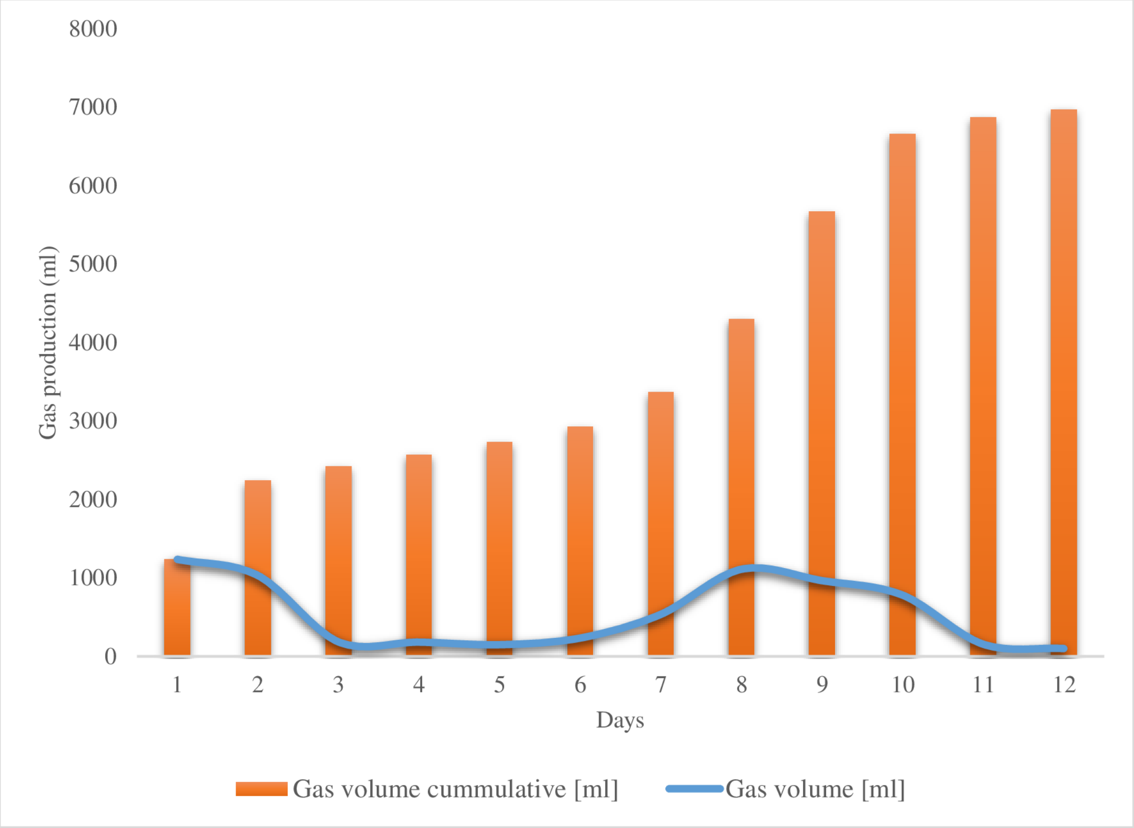

Figure 4.6: Biogas volume (ml) produced by inoculum 2: cassava waste 2

Source: Researcher's lab experiment (2024)

4.6.2. Biogas yield per day (litre)

Figure 4.7 presents the daily biogas production in litres for three different experiments involving various ratios of inoculum to cassava waste. In the experiment (Inoculum 2: Cassava 1), the daily biogas production fluctuated throughout the duration of the experiment. The highest daily production was recorded on day 2, with 1.38 litres, followed by a gradual decline over the subsequent days. Overall, the cumulative biogas production reached 3.58 litres by the end of the experiment.

In the Inoculum 2: Cassava 2 experiment, the daily biogas production also exhibited fluctuations, with the highest production recorded on day 1, totalling 1.24 litres. However, unlike the first experiment, the biogas production in this experiment continued to increase until day 8 before declining. The cumulative biogas production for this experiment reached 6.66 litres. Lastly, in the Inoculum 4: Cassava 1 experiment, the daily biogas production was consistently lower compared to the other two experiments. The highest daily production occurred on day 2, with 0.61 litres, but overall, the cumulative biogas production was much lower, totalling only 1.51 litres by the end of the experiment. However, the lowest daily biogas production was recorded in the control experiment where the daily biogas production declined from 0.0425 to 0.008 litres.

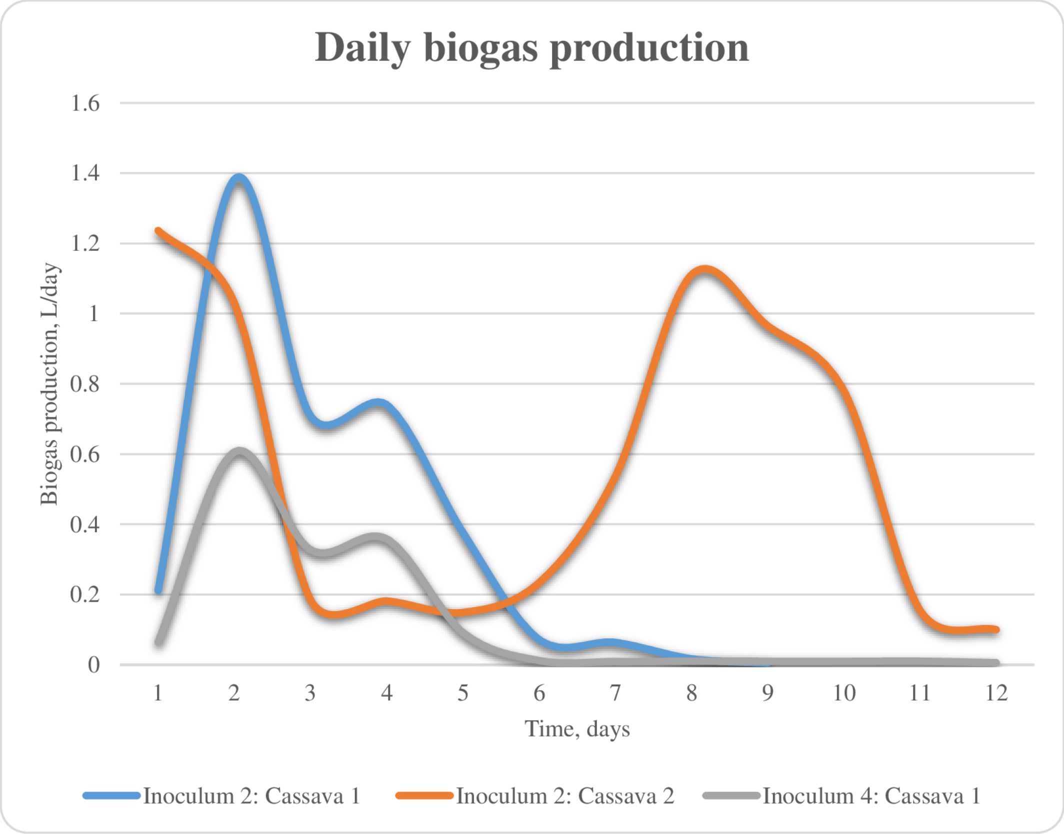

Figure 4.7: Biogas yield per day (litre)

Source: Researcher's lab experiment (2024)

4.6.3. Biogas cumulative yield (litre)

The result in Figure 4.8 represents the cumulative biogas volume (in litres) recorded over time in three different experiments, each with varying ratios of inoculum to cassava waste. In the first experiment (Inoculum 2: Cassava 1), the cumulative biogas volume increased steadily over time, reaching a maximum of 3.58 litres. This suggests that the ratio of inoculum to cassava waste used in this experiment was conducive to biogas production, as evidenced by the consistent increase in gas volume.

Similarly, in the second experiment (Inoculum 2: Cassava 2), the cumulative biogas volume also showed a steady increase over time, peaking at 6.97 litres. This indicates that the pH adjustment for the ratio of inoculum to cassava waste in this experiment varied with biogas production compared to the first experiment (Inoculum 2: Cassava 1). In contrast, the third experiment (Inoculum 4: Cassava 1) yielded lower cumulative biogas volumes overall, with a maximum of 1.52 litres. This suggests that the higher ratio of inoculum used in this experiment may not have been as effective for biogas production with cassava waste as a substrate.

The blank data remains relatively the lowest throughout the experiment, with gas volumes fluctuating around 0.008 to 0.053 litres, indicating minimal gas production in the absence of substrate.

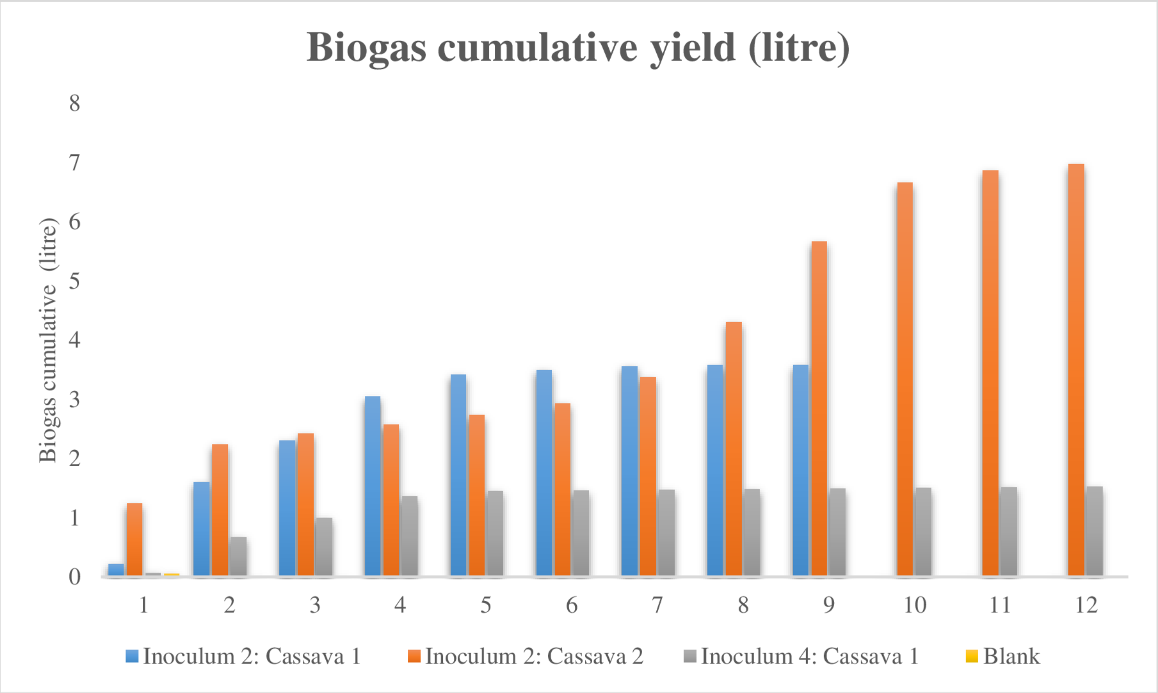

Figure 4.8: Biogas cumulative yield (litre)

Source: Researcher’s lab experiment (2024)

4.6.4. Methane (CH_4) yield per day (litre)

The result displayed in Figure 4.9 presents the daily methane yield in litres for three different experiments involving various ratios of inoculum to cassava waste. In the experiment "Inoculum 2: Cassava 1," the daily methane yield fluctuated throughout the duration of the experiment. The highest daily yield was recorded on day 4, with 0.45 litres, followed by a slight decrease over the subsequent days. Overall, the cumulative methane yield reached 1.55 litres by the end of the experiment.

In the "Inoculum 2: Cassava 2" experiment, the daily methane yield also exhibited fluctuations, with the highest yield recorded on day 7, totalling 0.73 litres. However, unlike the first experiment, the methane yield in this experiment continued to increase until day 8 before declining. The cumulative methane yield for this experiment reached 3.09 litres. Lastly, in the "Inoculum 4: Cassava 1" experiment, the daily methane yield was consistently lower compared to the other two experiments. The highest daily yield occurred on day 8, with 0.18 litres, but overall, the cumulative methane yield was much lower, totalling only 0.47 litres by the end of the experiment. In contrast, methane yield in the control experiment was the lowest ranging from 0.000176 litre to 0.001371 litre.

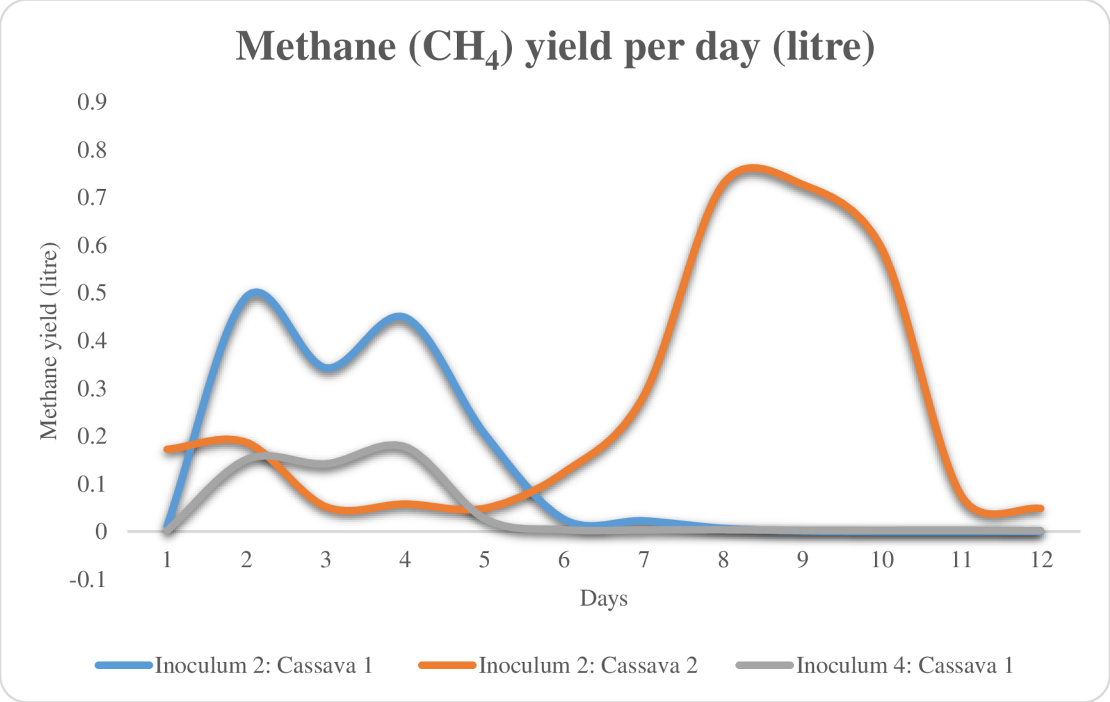

Figure 4.9: Methane (CH_4) yield per day (litre)

Source: Researcher's lab experiment (2024)

4.6.5. Cumulative methane (CH_4) yield

The result presented in Figure 4.10 shows the cumulative methane (CH_4) volume in litres over time for three different experiments involving various ratios of inoculum to cassava waste. In the first experiment (Inoculum 2: Cassava 1), the cumulative methane production steadily increased over time, reaching a maximum of 1.55 litres by the end of the experiment. This indicates that the ratio of inoculum to cassava waste used in this experiment was conducive to methane production, as there was a consistent and significant increase in methane volume over time.

Similarly, in the "Inoculum 2: Cassava 2" experiment, the cumulative methane production also increased over time, peaking at 3.09 litres. This experiment demonstrated a similar trend to the first experiment, with a steady increase in methane production throughout the duration. However, in the "Inoculum 4: Cassava 1" experiment, the cumulative methane production was notably lower compared to the other two experiments, reaching only 0.47 litres by the end of the experiment. This suggests that the higher ratio of inoculum to substrate used in this experiment may not have been as effective for methane production with cassava waste as a substrate.

Meanwhile. the blank data remains relatively lowest, indicating minimal methane production ranging from 0.000352 to 0.00159 litres, serving as a reference for background methane levels in the absence of substrate.

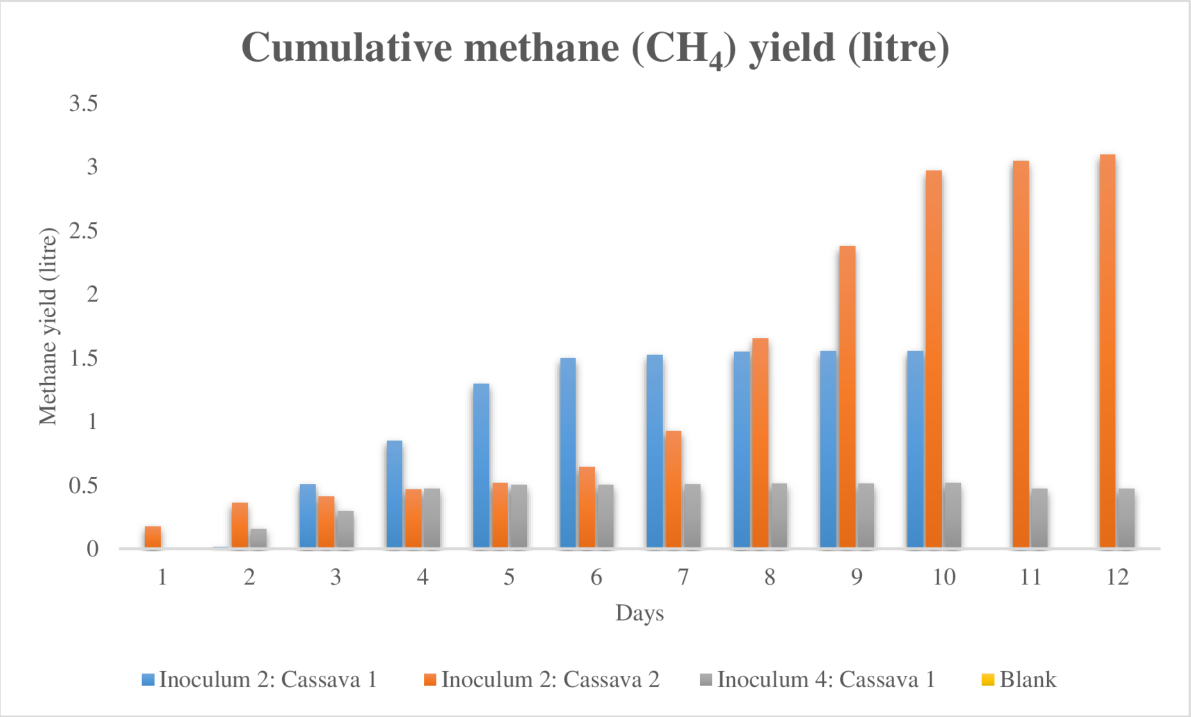

Figure 4.10: Cumulative methane (CH_4) yield (litre)

Source: Researcher's lab experiment (2024)

4.6.6. Cumulative Biogas and Methane (CH_4) yield (L/kgVs)

The result presented in Figure 4.11 represents the cumulative gas production and cumulative methane (CH_4) production in litre per kilogram of volatile solids (l/kgVs) for three different experiments involving various ratios of inoculum to cassava waste. In the experiment "Inoculum 2: Cassava 1," the cumulative gas production per kgVs reached 180.28 L/kgVs, while the cumulative methane production per kgVs was 78.32 L/kgVs. This indicates that a significant portion of the gas produced in this experiment was methane, which is the desired end-product of anaerobic digestion.

In the "Inoculum 2: Cassava 2" experiment, both the cumulative gas production per kgVs and cumulative methane production per kgVs were higher compared to the first experiment. Specifically, the cumulative gas production per kgVs reached 283.58 L/kgVs, while the cumulative methane production per kgVs was 125.97 L/kgVs. This suggests that the ratio of inoculum to cassava waste used in this experiment was more favourable for both overall gas production and methane production.

However, in the "Inoculum 4: Cassava 1" experiment, both the cumulative gas production per kgVs and cumulative methane production per kgVs were lower compared to the other two experiments. Specifically, the cumulative gas production per kgVs reached 85.93 L/kgVs, while the cumulative methane production per kgVs was 26.63 L/kgVs. This suggests that the lower ratio of substrate used in this experiment may not have been as effective for gas and methane production with cassava waste as a substrate.

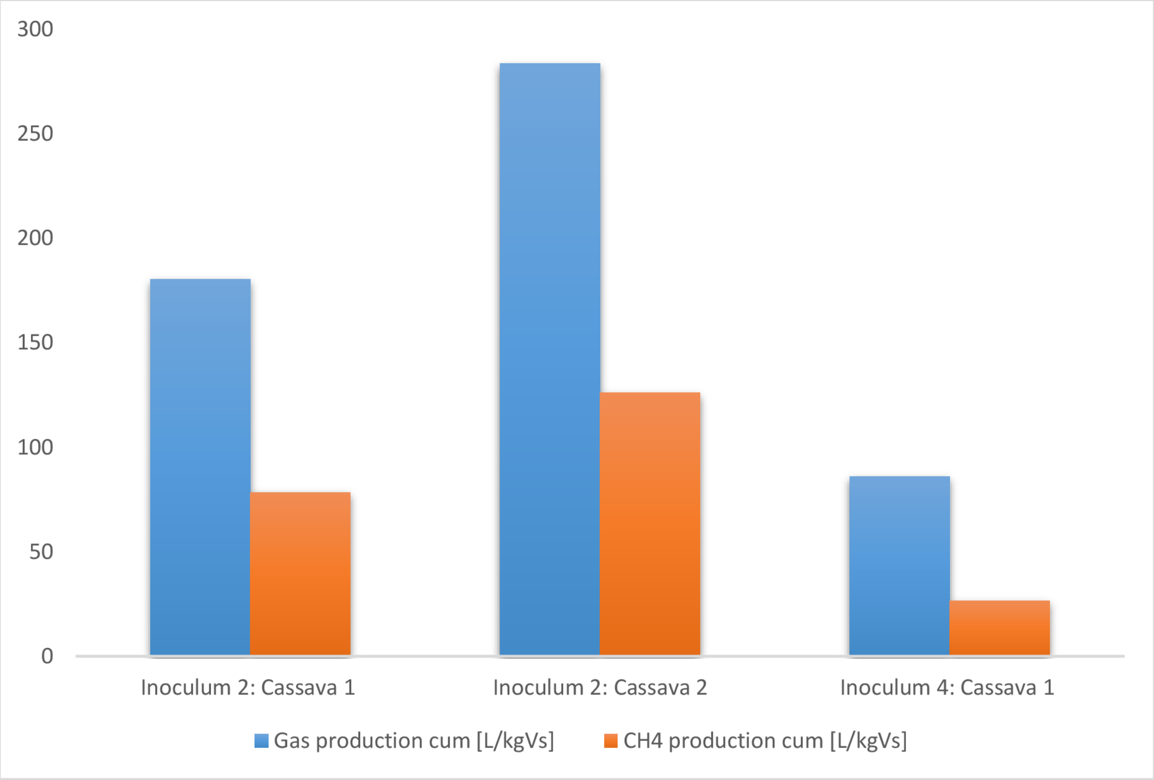

Figure 4.11: Cumulative Biogas and Methane (CH_4) yield (L/kgVs)

Source: Researcher’s lab experiment (2024)

4.6.7. Total Solids (TS) and Volatile Solids (VS) composition

Total solids (TS) represent the total amount of solids present in the mixture, including both organic and inorganic components, while volatile solids (VS) represent the organic fraction of the total solids that can be converted into biogas through anaerobic digestion. From the result, it is evident that there was a decrease in both TS and VS content from the 1st day to the 10th day across all conditions. This decrease suggests that there was degradation of organic matter during the fermentation process, likely due to microbial activity.

The initial TS and VS content varied between the different conditions, with the highest initial values observed in the "Inoculum 4: Cassava 1" condition. This higher initial organic content may have provided a greater substrate for microbial activity, potentially resulting in higher biogas yields. The decrease in TS and VS content over time indicates that the organic matter present in the mixture was being converted into biogas, primarily methane and carbon dioxide, through anaerobic digestion. The higher VS content compared to TS indicates that the majority of the solids present in the mixture were organic and therefore capable of contributing to biogas production.

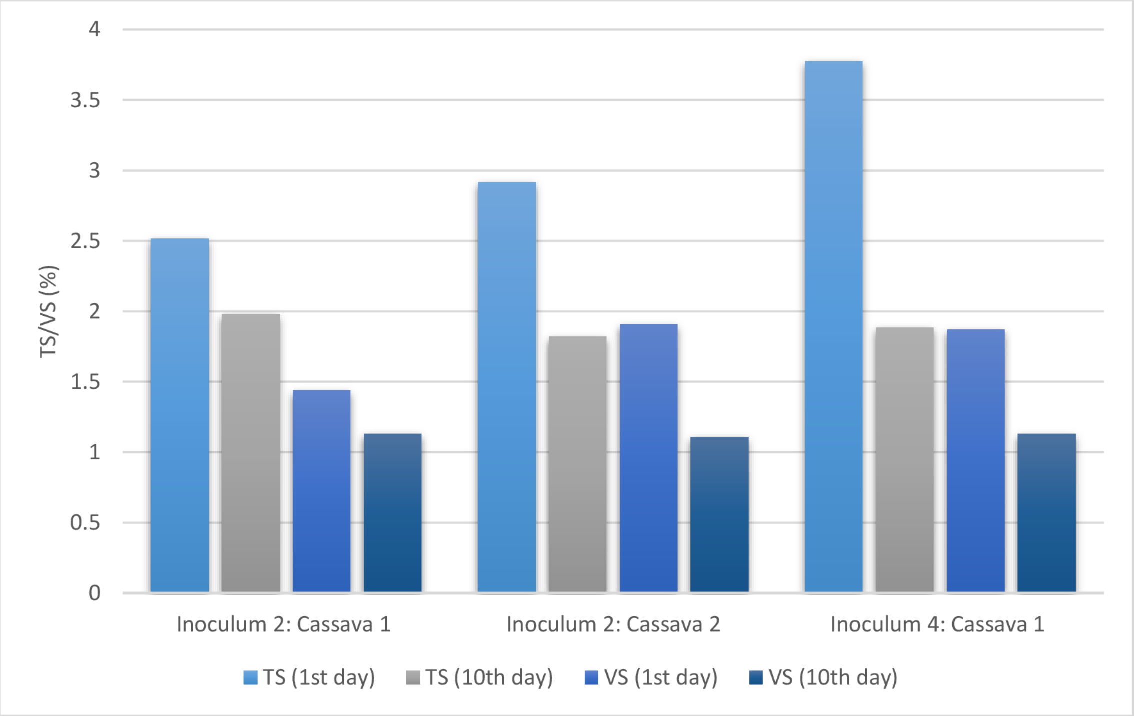

Figure 4.12: TS and VS (%) composition

Source: Researcher’s lab experiment (2024)

5. Discussion

5.1. Socioeconomic characteristics

The examination of socio-economic characteristics among participants in the cassava enterprise in Ilaro, Ogun State, Nigeria, reveals significant insights when juxtaposed with recent scholarly work. These findings illuminate not only the prevailing trends within agricultural demographics and socio-economic frameworks but also underscore the distinct nuances specific to the local context. Through this comparison, a complex portrait of agricultural participation emerges, characterized by gender balance, youthful engagement, and the pivotal role of marital status, all of which resonate with broader observations in agricultural research yet are distinctly shaped by local conditions and practices. This analysis not only contextualizes the Ilaro cassava enterprise within the larger agricultural landscape but also brings to the forefront the multifaceted nature of socio-economic influences on agricultural productivity and sustainability.

The gender balance observed in the cassava sector of Ilaro, with 53.7% male and 46.3% female participation, mirrors wider trends in agricultural engagement across various regions. Adebayo et al. (2023) noted similar gender inclusivity in Nigerian agricultural activities, emphasizing the growing recognition of the critical role women play in farming and agricultural productivity. This trend is significant as it signals a move towards more gender-inclusive agricultural policies and practices, which are essential for sustainable development.

The dominant presence of individuals within the 25-34 age bracket in the cassava enterprise underscores a broader shift towards the involvement of younger populations in agriculture, as observed by Kazeem et al. (2022). This demographic trend is particularly encouraging as it suggests a rejuvenation of the agricultural workforce with individuals who are potentially more open to innovation and adopting new technologies. Such a shift is crucial for the sustainability of agriculture in the face of challenges such as climate change and urbanization, which require innovative solutions and practices.

The marital status distribution, with a majority being married, reflects findings from Chukwuemeka et al. (2021), indicating a common pattern where family units play a significant role in agricultural productivity. The involvement of family members not only in labour but also in decision-making processes can enhance the resilience and adaptability of agricultural enterprises. Furthermore, the diverse demographic landscape characterized by a mix of genders, ages, and marital statuses in the cassava sector of Ilaro aligns with the findings of Adeniyi et al. (2024), who observed demographic diversity across West African agricultural sectors. This diversity is a strength, offering a mix of experience, perspectives, and resilience strategies that can contribute to the sector's overall productivity and sustainability.

The spectrum of educational attainment among participants—from those with no formal education to those with tertiary degrees—highlights a broad base of knowledge and skills enhancing the sector's productivity. This reflects findings by Omotoso and Fadairo (2021), who emphasize the significant role of education in improving agricultural efficiency, suggesting that a blend of formal education and practical experience can be particularly potent in agricultural settings.

Similarly, the household size data, with a prominent segment consisting of 3-4 members, suggests that the cassava enterprise is pivotal in supporting families of varying sizes, contributing to the economic well-being of the community. This aligns with Adekunle (2022) analysis on the impact of agriculture on household income and food security, reinforcing the idea that agricultural engagement, through both production and processing, is vital for enhancing household income levels and ensuring economic stability across different family structures.

Moreover, the distribution of enterprise types among the respondents—spanning cassava farming, processing, and those involved in both—reveals a strategic diversification within the cassava value chain. This multifaceted approach is key to building a resilient agricultural sector capable of sustaining economic growth and stability. Agboola et al. (2023) underscore this perspective, arguing that diversification across the value chain not only adds value but also strengthens the economic foundations of those involved in cassava enterprises, from farmers to processors.

The characteristics of the workforce in the cassava enterprise in Ilaro, Ogun State, Nigeria, particularly in terms of years of experience and income distribution, present a unique opportunity to delve into the dynamics that influence agricultural development and economic sustainability. A considerable portion of the workforce boasts a significant amount of experience, with a majority having between 6 to 10 years and a substantial group exceeding a decade in the field. This depth of experience is indicative of a stable and mature workforce, which is pivotal for the development and growth of the industry. However, the income distribution within this sector, notably the substantial disparity between the majority earning above ₦150,000 and a small fraction earning below ₦50,000, points to underlying socio-economic challenges.

The prevalence of a seasoned workforce in the cassava sector aligns with findings from Adewale et al. (2021), who observed that experience in agricultural practices often correlates with improved productivity and innovation adoption. This suggests that the experience within the cassava enterprise could be a critical asset in enhancing efficiency and adopting new technologies. Similarly, the study by Oseni and Winters (2022) on agricultural workforce dynamics in Sub-Saharan Africa corroborates the notion that a more experienced workforce can significantly contribute to agricultural resilience and adaptability, further emphasizing the strategic advantage of the workforce's maturity in Ilaro.

On the financial aspect, the income distribution within the cassava enterprise reflects broader economic trends observed in the agricultural sector of developing economies. The work of Iheke and Ochiaka (2023) highlights the income disparities within agricultural enterprises and the impact of such disparities on livelihood sustainability. Their analysis suggests that while a significant portion of the workforce might enjoy relatively stable incomes, the existence of individuals earning significantly less signals economic vulnerabilities that could undermine overall sector growth.

Furthermore, the research by Eze et al. (2024) on income diversification strategies among rural agricultural households in Nigeria suggests that diversification is a key strategy for addressing income disparities. This approach could be particularly relevant for the cassava enterprise in Ilaro, where targeted interventions aimed at promoting income-generating activities beyond primary production might help alleviate the identified income disparities.

5.2. Current practices and challenges in the management of cassava waste

The management practices for cassava waste among respondents in Ilaro, Ogun State, Nigeria, reveal a range of methods, from environmentally concerning practices like burning to more sustainable approaches such as selling waste, and using it as animal feed. This diversity in waste management strategies mirrors broader discussions in recent literature on agricultural waste management, sustainability, and environmental health.

Burning, employed by 47.3% of respondents, is identified as a prevalent but environmentally detrimental practice. Studies by Akindele et al. (2021) and Ojo and Adebayo (2022) highlight the negative impacts of open burning on air quality and the loss of biomass that could be utilized more productively. These concerns resonate with global calls for sustainable waste management practices that prioritize environmental health and resource conservation.

In contrast, the sale of cassava waste, as reported by 14.7% of respondents, points to an underexplored economic opportunity within the waste management spectrum. This aligns with research by Emeka and Okonkwo (2023), who argue for the valorization of agricultural waste into profitable ventures, suggesting that waste can be transformed into a resource, contributing to the circular economy and enhancing community economic development.

The use of cassava waste as animal feed, both in its dry (9.3%) and wet (11.3%) forms, reflects an integration of waste management with agricultural sustainability, a practice supported by the findings of Nwankwo et al. (2024). These authors demonstrate how converting agricultural by-products into livestock feed not only reduces waste but also supports local farming economies by decreasing feed costs and enhancing sustainability.

However, the fact that 17.3% of respondents discard cassava waste highlights a critical gap in knowledge or resources for implementing more sustainable waste management practices. This observation is echoed in the work of Adewumi and Oladele (2022), who suggest that increased education and awareness are fundamental to shifting towards more sustainable practices, emphasizing the role of knowledge dissemination in fostering environmental stewardship within agricultural communities.

These findings suggest that while there are segments of the cassava enterprise workforce in Ilaro engaged in sustainable waste management practices, there remains a significant proportion of individuals relying on practices that are environmentally unsustainable. Encouraging a shift towards more sustainable methods, through education, awareness, and the promotion of economic opportunities, could enhance environmental health and contribute to the economic development of the community.

The challenges reported by respondents regarding cassava waste management in Ilaro, Ogun State, Nigeria, reflect a complex interplay of economic, infrastructural, environmental, and knowledge-based factors that impact the viability and efficiency of waste utilization practices. The high cost of labour, as indicated by 16% strongly agreeing and 64.3% agreeing, underscores a significant concern among respondents regarding the economic burden associated with waste management. This resonates with findings from studies such as Ogunbanwo and Oluyemi (2023), which discuss the economic implications of labour costs in agricultural production, emphasizing the need for strategies to mitigate labour expenses while enhancing productivity.

Similarly, the consensus among respondents (68.3% strongly agreeing and 23% agreeing) regarding the low market demand for cassava waste products highlights a significant challenge in converting waste into valuable products. This aligns with the findings of Ajani et al. (2022), who explore market challenges in the agricultural sector, emphasizing the importance of market access and value chain development in promoting waste utilization as a viable economic endeavour.

The shortage of waste-disposing pits in processing areas, acknowledged by 67.3% of respondents, indicates an infrastructural bottleneck that hinders effective waste management practices. This infrastructural challenge echoes discussions in the literature, such as the work of Olajide and Adekunle (2021), which emphasizes the critical role of infrastructure in supporting sustainable agricultural practices and waste management.

Moreover, the recognition of inadequate water for effluent washing by 60% of respondents underscores environmental considerations and resource limitations in waste management processes. This aligns with studies by Lawal and Ajayi (2023), which discuss the environmental implications of inadequate water resources in agricultural activities, emphasizing the importance of water conservation and management strategies in sustainable agriculture.

Furthermore, the acknowledgment of inadequate knowledge and limited access to extension agents by a majority of respondents (69.7%) highlights the critical role of education and support in improving waste management practices. This aligns with research by Fadairo et al. (2022), which emphasizes the importance of extension services in disseminating information and promoting best practices in agricultural waste management.

The perception of weather-related challenges, such as seasonal sunshine constraints for sun-drying cassava waste, by a considerable proportion of respondents (19.7% strongly agreeing and 36.7% agreeing) underscores the impact of climatic factors on waste utilization practices. This aligns with discussions by Olaniyi et al. (2022), which examine weather variability and its implications for agricultural production, highlighting the need for climate-resilient waste management strategies.

5.3. Awareness regarding the potential of cassava waste for biogas production

The findings regarding awareness of improved methods for cassava waste utilization among respondents in Ilaro, Ogun State, Nigeria, underscore both encouraging progress and remaining challenges in promoting sustainable practices within the community. The substantial majority of respondents, accounting for 77.3%, expressing awareness of innovative approaches indicates a commendable level of knowledge and engagement with sustainable waste management practices. This aligns with broader discussions in recent literature on agricultural extension services and awareness campaigns. For instance, the work of Adeyemo et al. (2021) emphasizes the importance of targeted education and information dissemination in enhancing agricultural practices and promoting sustainability. Similarly, studies by Onyango et al. (2022) highlight the effectiveness of community-based outreach programs in increasing awareness and adoption of sustainable agricultural techniques. These findings suggest that existing efforts to raise awareness about improved cassava waste utilization methods have yielded positive results, contributing to a more informed and knowledgeable community.

However, the acknowledgment by 22.7% of respondents of a lack of awareness regarding advanced cassava waste management methods signals a remaining awareness gap that needs to be addressed. While this segment represents a smaller proportion of the surveyed population, it highlights the importance of continuous education and outreach efforts to ensure that all community members have access to information on sustainable practices. This finding resonates with research on knowledge dissemination in agricultural contexts. For instance, the study by Idris et al. (2023) emphasizes the need for tailored extension programs that target specific knowledge gaps and ensure equitable access to information among diverse demographic groups. Similarly, the work of Asante et al. (2021) underscores the role of community engagement and participatory approaches in promoting sustainable agricultural practices, emphasizing the importance of inclusive communication strategies that reach all stakeholders.

The findings regarding cassava waste utilization methods among respondents in Ilaro, Ogun State, Nigeria, shed light on the diverse and innovative approaches adopted by the community, reflecting a multifaceted engagement with sustainable agricultural practices. The predominance of cassava waste utilization as animal feed, reported by 55.0% of respondents, underscores the dual benefits of waste management and resource production for livestock farming, aligning with principles of sustainable agriculture. This finding resonates with broader discussions in recent literature on agricultural sustainability. For instance, studies by Olaniyi et al. (2021) and Ogunmola and Adeyemo (2022) highlight the importance of utilizing agricultural by-products as feed resources to enhance livestock productivity while reducing waste. These findings suggest that the adoption of cassava waste as animal feed reflects a commitment to resource efficiency and environmental stewardship within the community.

Moreover, the diversity in cassava waste utilization methods reported by respondents highlights the innovative approaches being employed to address waste management challenges while creating economic opportunities. The adoption of mushroom production by 10.0% of respondents is particularly noteworthy, as it not only contributes to waste management but also presents the potential for economic value addition through the sale of mushrooms. This aligns with research by Asante and Mensah (2021), who discuss the economic potential of mushroom cultivation as a sustainable livelihood strategy in agricultural communities. Additionally, the utilization of cassava waste for biogas and ethanol production, reported by 10.7% and 7.7% of respondents, respectively, reflects an environmentally conscious approach to waste management, converting organic waste into renewable energy sources. These findings align with discussions on bioenergy production and waste-to-energy technologies in the agricultural sector, emphasizing the role of renewable energy in promoting sustainable development and mitigating environmental impacts.

Furthermore, the utilization of cassava waste for fertilizer production, reported by 16.7% of respondents, underscores a commitment to enhancing agricultural productivity through sustainable practices. This method not only contributes to waste management but also supports soil fertility, aligning with broader goals of promoting eco-friendly and nutrient-rich farming practices. This finding resonates with research on organic fertilizer production and soil health management in agricultural systems. For instance, studies by Idris et al. (2022) and Ojo and Abiodun (2023) emphasize the importance of organic amendments in improving soil fertility and crop productivity while minimizing environmental risks associated with chemical fertilizers.

The findings regarding the willingness to adopt biogas technology among respondents in Ilaro, Ogun State, Nigeria, reveal a significant level of support and enthusiasm for sustainable energy solutions within the community. The substantial majority, comprising 80.0% of respondents, expressing a strong willingness to adopt biogas technology indicates a proactive and environmentally conscious mindset among community members. This overwhelming support suggests a shared commitment to reducing environmental impact and embracing alternative energy sources that promote sustainability. These findings align with discussions in recent literature on renewable energy adoption and environmental awareness. For instance, studies by Ogunlana and Adekunle (2021) and Adelakun et al. (2022) emphasize the importance of community engagement and awareness campaigns in promoting renewable energy adoption and fostering environmental stewardship. These findings suggest that the high percentage of respondents willing to adopt biogas technology reflects a community that is open to innovation and committed to transitioning towards a more sustainable and eco-friendly energy landscape.

However, it is noteworthy that 20.0% of respondents indicate a reluctance or lack of willingness to adopt biogas technology. While this represents a smaller proportion of the surveyed population, it underscores the presence of barriers or concerns that may hinder widespread adoption of biogas technology within the community. This finding resonates with discussions on the challenges and barriers to renewable energy adoption in developing countries. For instance, research by Akindele and Olufemi (2022) and Okonkwo et al. (2023) highlight factors such as affordability, accessibility, and technological complexity as potential barriers to renewable energy adoption, particularly in rural areas. Addressing these concerns and barriers through targeted education, policy support, and financial incentives is essential for overcoming resistance and promoting broader acceptance of biogas technology among community members.

5.4. Perceptions of cassava stakeholders on adoption of biogas

The perceptions and attitudes of stakeholders regarding the adoption of biogas technology in Ilaro, Ogun State, Nigeria, reveal both opportunities and challenges in transitioning towards sustainable energy solutions. The overwhelming consensus among stakeholders regarding the potential benefits associated with biogas adoption, such as improved energy security, environmental benefits, and income generation opportunities, underscores a positive response to the technology's potential impact. These findings resonate with discussions in recent literature on renewable energy adoption and sustainability, emphasizing the multifaceted benefits of biogas technology for communities, the environment, and the economy (Kemausuor et al., 2021; Meng et al., 2023).

However, significant concerns about the financial burden associated with high investment and running costs, uncertainty regarding economic benefits, and a lack of information and technical know-how emerge as prominent barriers to adoption. These barriers highlight the need for targeted interventions, including financial incentives, awareness campaigns, capacity-building initiatives, and supportive government policies, to address knowledge gaps, alleviate financial constraints, and facilitate the widespread adoption of biogas technology (Abunyewa et al., 2022; Kimani et al., 2023). By addressing these barriers comprehensively, stakeholders can unlock the full potential of biogas technology to promote energy sustainability, environmental stewardship, and economic development within the community.

5.5. Biogas yield of cassava waste

The findings on biogas production from cassava peel correlate well with established research. Similar to other studies, there was a low initial gas yield followed by a sharp rise, reflecting microbial adaptation and exponential growth. This aligns with the observations of Haven & Gooch, (1991] and Nayak and Singh, (2015). A slight decline in gas production on days 3 and 4, potentially due to substrate depletion or environmental changes, is consistent with what Banks et al. (2011) reported. Finally, the gradual decrease towards the end (days 8 and 9) matches the nutrient depletion and by-product inhibition observed by Eskicioglu et al. (2007) and Zhang et al. (2013).

The findings of this research also align well with established knowledge on the importance of inoculum to cassava waste ratio for biogas production. Similar to other studies (Xiao et al., 2018; Nayak & Singh, 2015), a moderate inoculum amount (Exp. 1, 2:1 ratio) resulted in a steady increase in biogas, indicating sufficient microbes for efficient breakdown. Interestingly, Experiment 2 (2:2 ratio) showed an even higher yield, suggesting a potential optimal range for inoculum concentration. This aligns with Mata-Alvarez et al. (2014) who found that exceeding a certain ratio can limit nutrients or hinder microbes. Finally, the significantly lower output in Experiment 3 (4:1 ratio) confirms that the lack of substrate limits the growth of methanogenic bacteria mirroring observations by Chen et al. (2017) where excessive inoculum in food waste digestion led to decreased biogas production. This study therefore reinforces the importance of finding the optimal inoculum to cassava waste ratio for maximizing biogas output.

The decrease in both total solids (TS) and volatile solids (VS) across all conditions (Exp. 1, 2 & 3) from day 1 to day 10 indicates that organic matter was being broken down, likely by microbes. This is similar to what Li et al. (2017) and Nayak & Singh (2015) observed in other studies on lignocellulosic biomass digestion. The decrease in VS over time reflects the conversion of organic matter into biogas (mainly methane and carbon dioxide) during digestion, as explained by Chen et al., 2017).

6. Conclusions

The findings of this study revealed a diverse workforce in terms of gender, age, and education among cassava enterprises in Ilaro, Nigeria. This reflects a move towards more inclusive and potentially innovative agricultural practices. The prevalence of family units and a range of educational backgrounds highlight the importance of social structures and knowledge in this sector. While there's experience within the workforce, income disparities exist. Cassava waste management practices in Ilaro vary considerably. Burning waste is common, but unsustainable. Selling waste or using it for animal feed offers economic and environmental benefits. However, a significant portion of waste is discarded, indicating a need for promoting sustainable practices through education and economic incentives.

The challenges of sustainable cassava waste management in Ilaro are multifaceted. These include economic concerns like labour costs and limited market demand for waste products. Additionally, infrastructural limitations, such as the lack of proper waste disposal pits, and environmental considerations, like water scarcity, hinder effective waste management. Furthermore, inadequate knowledge and limited access to support services create another hurdle. Even weather patterns can impact waste utilization practices. Despite these challenges, there's encouraging progress in promoting sustainable cassava waste utilization. A significant portion of the community is aware of innovative approaches, like using cassava waste for biogas production or mushroom cultivation. These practices offer environmental and economic benefits. The willingness to adopt biogas technology is also high, reflecting a commitment to sustainable energy solutions. However, some barriers remain, and addressing these concerns is crucial for widespread adoption.

The experiment conducted to determine the biogas yield of cassava waste in a mixture of inoculum has provided valuable insights into the potential of cassava waste as a feedstock for anaerobic digestion. Through a comprehensive analysis of various parameters including gas production, methane yield, total solids (TS) and volatile solids (VS) content, as well as the ratio of inoculum to cassava waste, several important conclusions can be drawn. Firstly, it was observed that the cumulative gas production and methane yield increased over time in all experiments, indicating the effectiveness of the anaerobic digestion process in converting organic matter into biogas. The highest cumulative gas production and methane yield were observed in the experiment with the ratio of Inoculum 2: Cassava 2, suggesting that this ratio was more favourable for biogas production compared to the other ratios tested and may be attributed to the increased amount of available substrate, but it also affected the fluctuating pH values that need more attention and possible adjustment during the fermentation process. This finding highlights the importance of optimizing the ratio of inoculum to substrate to maximize biogas yields.

Furthermore, the analysis of TS and VS content provided insights into the degradation of organic matter during the fermentation process. A decrease in both TS and VS content from the 1st day to the 10th day was observed in all experiments, indicating that the organic matter present in the mixture was effectively utilized by the microbial community for biogas production.

Additionally, the experiment demonstrated that cassava waste is a promising substrate for anaerobic digestion, with the potential for sustained and significant biogas yields over time. The availability of cassava waste as a feedstock for biogas production offers opportunities for waste management and renewable energy generation, contributing to both environmental sustainability and energy security. However, it is important to note that further optimization of the fermentation conditions and monitoring of factors such as substrate composition, pH, and temperature may be necessary to maximize biogas production and ensure consistent yields in practical applications. Additionally, variations in substrate characteristics, such as the ratio of inoculum to cassava waste and TS/VS content, can significantly impact biogas production efficiency and should be carefully considered in future experiments and industrial-scale applications.

In conclusion, the experiment has provided valuable insights into the biogas potential of cassava waste and the factors influencing biogas production. The findings contribute to our understanding of anaerobic digestion processes and offer opportunities for the development of sustainable waste management and renewable energy solutions. Further research and optimization efforts are warranted to fully unlock the potential of cassava waste as a feedstock for biogas production and realize its benefits on a larger scale.

6.1. Recommendations

Based on the findings of this study, the following recommendations were made:

i. Promote gender-inclusive agricultural policies and practices: The research suggests a balanced participation of men and women in cassava enterprises. Enhancing this trend through targeted policies and initiatives can unlock the full potential of the agricultural workforce.

ii. Develop programs to attract young people to agriculture: The study highlights a shift towards younger generations entering the sector. Creating programs that provide education, training, and resources can further incentivize youth participation and bring fresh perspectives to agricultural practices.

iii. Offer educational programs on sustainable cassava waste management: A significant portion of the workforce lacks knowledge about sustainable waste management practices. Developing educational programs can address this gap and equip farmers with the tools and techniques to minimize environmental impact.

iv. Explore economic opportunities for cassava waste utilization: The research identified the potential for selling cassava waste products and converting them into valuable resources like biogas and fertilizer. Encouraging research into these areas and exploring market opportunities can generate additional income streams for cassava enterprises.

v. Invest in infrastructure development for cassava processing areas: The lack of proper waste disposal pits and limited water resources were identified as challenges. Investing in infrastructure development can improve sanitation, facilitate effective waste management, and promote water conservation practices.

vi. Strengthen agricultural extension services: The study revealed a need for improved access to knowledge and support services. Strengthening extension services can provide farmers with access to experts who can offer guidance on sustainable practices, new technologies, and best practices in cassava waste management.

vii. Provide financial incentives for the adoption of biogas technology: While there's a willingness to adopt biogas technology, economic concerns remain a barrier.

Introducing financial incentives, such as subsidies or low-interest loans, can make biogas technology more accessible and encourage wider adoption within the cassava enterprises.

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Appendices

Appendix 1: Pictorial evidences of the laboratory experiment


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