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Anaerobic Co-digestion of Palm Oil Sludge, Cassava Peels, Cow Dung and Ground Eggshells: Process Optimization and Biogas Generation

D. O. Olukanni[1], M. J. Kamlenga[2]†, C. N. Ojukwu[1] and T. Mkandawire[3]
[1]Department of Civil Engineering, College of Engineering, Covenant University, Ota, Nigeria
[2]Department of Civil Engineering, Arusha Technical College, Arusha, Tanzania
[3]Department of Civil Engineering, Malawi University of Business and Applied Sciences, Blantyre, Malawi
†Corresponding author: M.J. Kamlenga; mwigine.kamlengapgs@stu.cu.edu.ng

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ABSTRACT

Indiscriminate disposal of crop and animal wastes has grown in acceptance across the globe as an environmentally hazardous practice. This study used a 225L polyethylene digester that was specially made to produce biogas from anaerobic co-digestion of palm oil sludge, cassava peels, and cow dung using ground eggshells for pH stabilization and a greenhouse for temperature control. Cassava peels, palm oil sludge, cow dung, and water were combined in a ratio of 1:1:2:5.3, respectively, and 1.3 kilograms of crushed eggshells were added. The bio-digestion system generated 650.60 L of cumulative biogas throughout the 30-day sludge retention period. The pH averaged 6.0, and the slurry temperature averaged 34.76°C during digestion, which is favorable for the production of biogas since microbial populations thrive under hospitable conditions. The biogas produced after a hydraulic retention time (HRT) of over 20 days had the highest methane concentration of 60%, while days under 10 HRT had the lowest methane content of 45.5%. On the 13th day of anaerobic digestion, biogas output peaked at 34.90L, and pH and temperature were maintained at 6.5 and 35.0°C, respectively, the ideal ranges for a healthy process. An efficient technique for producing energy in the form of biogas was shown by optimized anaerobic co-digestion of animal and crop waste utilizing ground eggshells and a greenhouse for pH and temperature control. Future research should focus on developing more efficient, cheaper microbial agents, such as enzymes for biological pre-treatment of palm oil sludge to reduce lignin, which negatively impacts biogas generation.

INTRODUCTION

The world's rising population has been linked to an increase in energy demand since more agricultural goods need to be processed to meet food demand, which leads to tremendous waste generation and environmental pollution. According to Olukanni et al. (2018), the generation of solid waste is rising faster than waste management programs put in place by organizations with sound financial and technical standing. Municipal waste, agricultural waste, and animal waste, all of which contain organic materials, are examples of solid wastes created (Giwa et al. 2017). The tropical climate favors the growth of crops such as cassava, palm oil, maize, cocoyam, yam groundnut, sorghum, cocoa, and cotton (Anh et al. 2022). When these crops are processed, wastewater, sediments, and peels are produced. All of these waste products are disposed of, and some are even eaten by cattle (Olukanni & Olatunji 2018). The peels and sludge that are discarded damage the atmosphere by giving off unpleasant odors. In addition, these wastes can contaminate the soil and surface water when rain washes them away because they contain acid (Omilani et al. 2019).

Appropriate handling and treatment of crop wastes (CW) have emerged as a global trend in many nations because they pollute the environment (Pramanik et al. 2019). In accordance with a study by De Clercq et al. (2017), the disposal of agricultural waste in landfills causes the production of large volumes of greenhouse gases (GHGs), such as carbon dioxide (CO_2) and methane (CH_4). The release of GHGs into the atmosphere, where CH_4 is 25 times more hazardous than CO_2, is thought to be the primary contributor to global warming (Slorach et al. 2019). Developing a proper management system of organic waste to recover biogas can be a breakthrough for developing nations that have a deficit in clean cooking energy, which leads to continuous deforestation and hence releases over 50 million tons of carbon dioxide emissions (Nwafor 2021). Due to inadequate energy sources, people are forced to rely on wood and charcoal as a source of energy for cooking, which leads to indoor air pollution and a variety of health problems, such as lower respiratory tract infections and chronic obstructive pulmonary disorders (US EPA 2013).

Appropriate handling of agricultural and animal wastes is one that Nations must address (Fagbenle & Olukanni 2022). The adequate management of cow dung (CD) has not been established recently, it has either been used without treatment, neglecting the expected implications on groundwater and soil contamination (Almomani & Bhosale 2020). Numerous techniques, such as anaerobic digestion (AD) (Almomani et al. 2017, 2019), composting (Guerra-Rodríguez et al. 2001), incineration (Demirer & Chen 2004), and soil application (Araji et al. 2001) were utilized to handle organic wastes. Up to a certain point, incineration is convenient, but it still has low productivity, poor energy__ value, and significant environmental problems in addition to greenhouse gas (GHG) emissions (Almomani & Bhosale 2020). Application to soil results in a significant loss of biomass, high carbon dioxide (CO_2) levels, and unpleasant odors that attract fungi and viruses that propagate disease (Xiao et al. 2013). Furthermore, composting emits greenhouse gases (GHG), results in the loss of nitrogen that is already present, and necessitates a suitable site with adequate protection from rainfall (Jacobs et al. 2019, Ren et al. 2019). To benefit the environment and take environmentally beneficial actions, it is necessary to find the appropriate conditions for using the energy value of cow dung and crop wastes.

Since 1870, AD has been one of the traditional methods used to treat a variety of wastes, including cow dung (CD) and crop wastes (CW) (LoraGrando et al. 2017). While other developed nations like Germany, the United States of America (USA), and Switzerland are pioneering with biogas plants supplied by anaerobic digestion systems, households living in villages in Asia have been using miniature anaerobic digesters to generate energy for use in cooking and lighting (Parthiba Karthikeyan et al. 2018, Vasco-Correa et al. 2018). As a result, it is vital to highlight the use of AD among the various biomass processes to satisfy the rising demand for energy worldwide (Khalid et al. 2011). The utilization of AD technology to process organic wastes with lower GHG emissions and produce renewable energy is a proven engineering principle (Zhang et al. 2019). Biogas is frequently formed as a result of the anaerobic breakdown of organic waste and other materials by a wide variety of bacterial species in the absence of oxygen (Chuichulcherm et al. 2017).

To maintain the mesophilic condition while enhancing the production of methane (CH_4) in the solid-state anaerobic co-digestion, cucumber wastes, and dairy manure were added at a feedstock-to-inoculum ratio of 1:1 (Li et al. 2021). Additionally, Dima et al. (2020) carried out anaerobic co-digestion of sugar beetroot root waste, cow dung, and chicken manure under mesophilic conditions in 30 days HRT, and the greatest output of methane was obtained ranging from 105.32 $mL.g^{-1}$ VS to 356.10 $mL.g^{-1}$ VS. Furthermore, the anaerobic digestion of rice straw in a reactor with a capacity of 300,000 liters resulted in the volumetric biogas of 323,000 liters per ton of dry rice straw (Zhou et al. 2017). Aside from lighting and cooking, manufactured biogas may also be used as gasoline for internal combustion engines and as a source of heat or power through the use of boilers and generators, among other things (Kadam & Panwar 2017). The biogas produced by anaerobic digestion contains a variety of different elements, depending on the type of organic wastes used as feedstock, with the majority being from 50 to 75% methane (CH_4), 25 to 50% carbon dioxide (CO_2), and other gases like 0 to 3% hydrogen sulfide (H_2S), 0 to 2% oxygen (O_2), 0 to 1% hydrogen (H), and 0 to 10% nitrogen (N_2) (Fagbenle & Olukanni 2022, Oladejo et al. 2020).

It has been shown that anaerobic co-digestion of biodegradable waste, such as crop wastes and cow dung, is an effective technique that might increase the production of biogas by over 80% (Braun et al. 2003). Because they contain a variety of nutrients, including the nitrogen that methanogens need, as well as a significant amount of buffering capacity, cow dung and other livestock manures are considered to be potential co-substrates (Moral et al. 2008). Anaerobic co-digestion provides the perfect environment for digestion by resolving a variety of practical difficulties such as pH, inhibition, carbon-to-nitrogen ratio (C: N) limits, substrate breakdown, and moisture content (MC) (Alkaya & Demirer 2011, Xu et al. 2018). Moreover, the ratios of CW and CD to be mixed, the makeup of the feedstocks to be blended, and the presence of low inert organic matter are additional key factors for the beneficial outcomes of anaerobic co-digestion (Almomani & Bhosale 2020). The purpose of this study was to investigate the anaerobic co-digestion of cow dung, cassava peels, and palm oil sludge to produce biogas while utilizing ground eggshells to maintain the pH and a specially-made reactor housed in a greenhouse to regulate the temperature.

MATERIALS AND METHODS

Description of the Anaerobic Bio-digester

As shown in Fig. 1, the 225L Polyethylene (PE) digester served as a single-stage anaerobic bio-digester for thirty days, during which sludge was retained. The design included one inlet (1) for loading feedstock and three outlets: the top outlet, the center outlet, and the bottom outlet. The first outlet

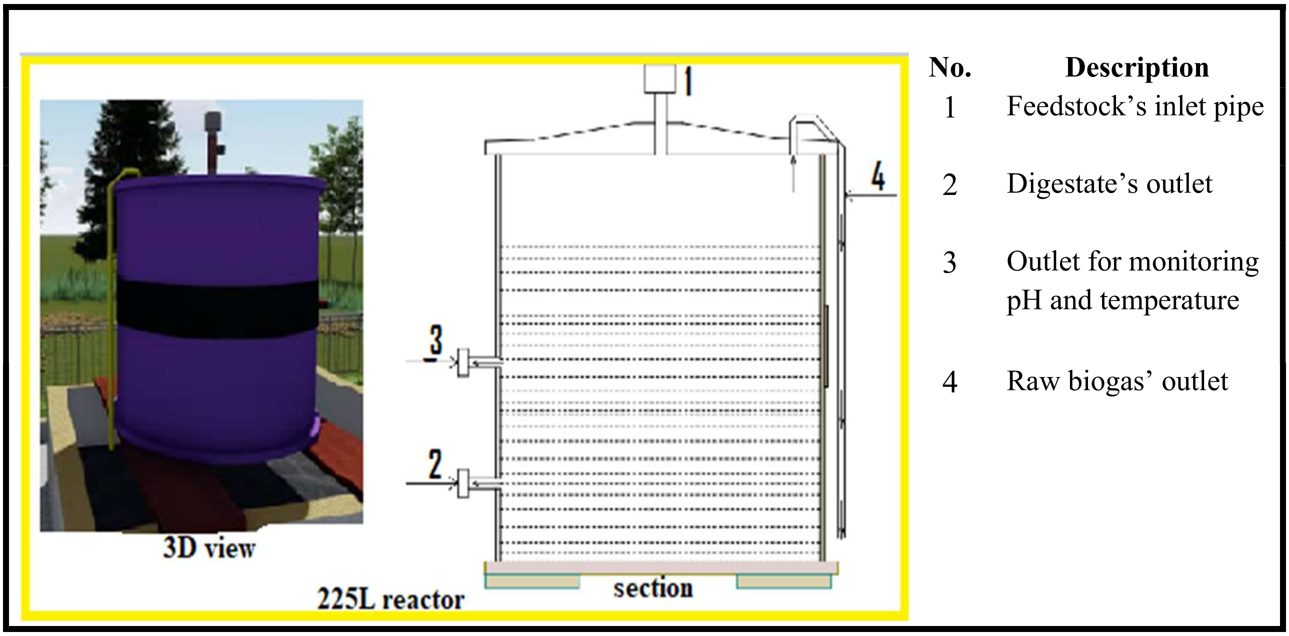

Fig. 1: The anaerobic bio-digesters schematic diagram.

(4) was connected to a gas pipe to collect the digester's raw biogas; the second outlet assisted (3) with daily monitoring by providing a location to collect slurry samples to determine pH and temperature; and the third outlet (2) was utilized to discharge the digestate once the digestion process was finished.

Substrates and Inoculum

Crop wastes, including cassava peels and palm oil sludge produced during the pressing of palm tree fruits to produce palm oil, were used as substrates. This experiment used cow dung from an abattoir in Ota, Ogun State, Nigeria, as the inoculum. Cassava peels were collected in Owode, Ogun State, while palm oil sludge was acquired from a mill at Covenant University in Canaanland, Ogun State, Nigeria. Before and following the anaerobic digestion (AD) procedure, samples of the substrates and inoculum were collected and examined, and their compositions were determined.

Methods of Analysis and Optimization of Process-Affecting Variables

15 kg of cassava peels and 15 kg of palm oil sludge were thoroughly combined in a weight-based ratio of 1:1. As an inoculum, 30 kg of cow dung was added to the substrate mixture in a weight-based ratio of 1:2. After that, the mixture of substrates and inoculum was combined with the freshwater volume of 80 liters. This created the ideal ratio of 1:1:2:5.3 for the corresponding amounts of cassava peels, palm oil sludge, cow dung, and water. 1.3 kg of ground eggshell was added to the slurry to regulate the pH value since they stop affecting the anaerobic digestion process when the pH value reaches 6.8, which is within the permitted range of 6.5 to 8.5 (Jain et al. 2015, Kumar & Samadder 2020). The physiochemical parameters including carbohydrates, proteins, lipids, total solids (TS), volatile solids (VS), total carbon (TC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), volatile fatty acids (VFAs) of sludge before and after digestion were measured using AOAC 931.02, AOAC 930.25, AOAC 922.06, APHA 4500-1, APHA 4500-1, ASTMD5907-04, AOAC 930.25, Spectrophotometry, AOAC 977.29, and IS 548:2010 respectively (Pramanik et al. 2019). The substrate sludge was manually mixed during the digestion phase, and a multimeter (HI 9813-5) was used to measure the pH and temperature of the slurry every day. The mesophilic state, which is between 30°C and 45°C (Zhang et al. 2017), was maintained as the optimal temperature for the anaerobic digestion process at about 34.76°C. To maintain this interior temperature range, the anaerobic bio-digester was erected in a greenhouse made of clear plastic sheets, as illustrated in Fig. 2.

Biogas Collection and its Purification Strategy

Fig. 3 illustrates the method used to collect and store the raw biogas produced during the anaerobic digestion phase using 175/65 R14 tire tubes.

Methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) concentrations in the collected biogas were

Fig. 2: Greenhouse for raising an anaerobic bio-digester.

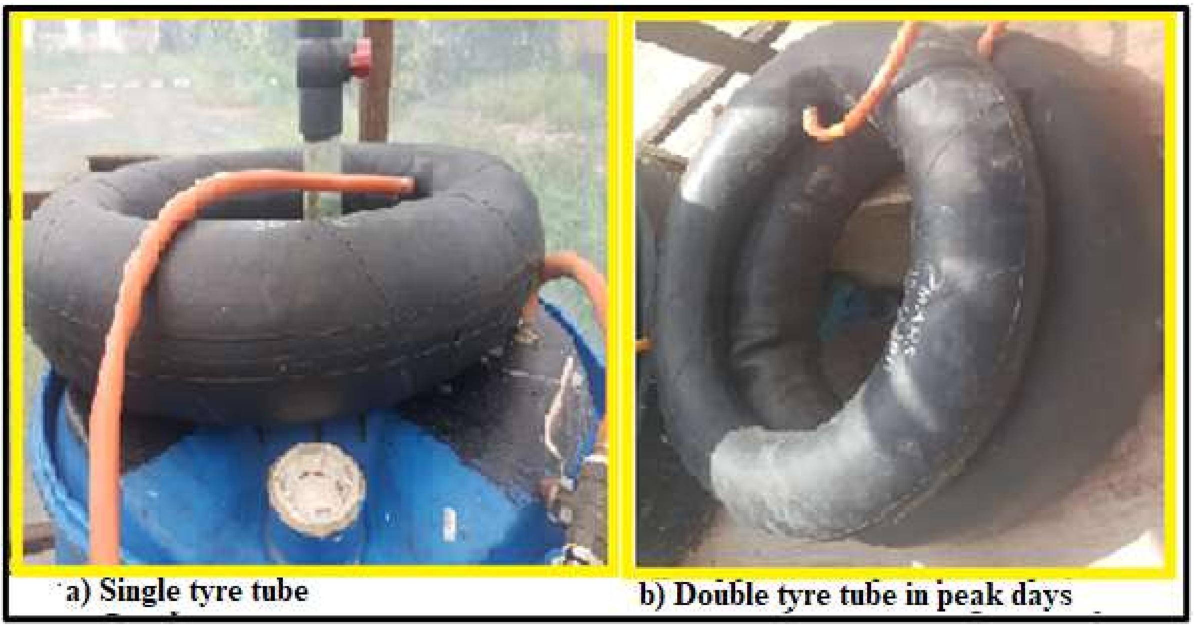

Fig. 3: Biogas-filled 175/65 R14 tyre tube.

measured both before and after the purification procedure using the biogas analyzer (GFM Series). The quantity of these components was measured and compared to limits provided in the literature to provide recommendations for the usage of such biogas in daily life.

The purification protocol that was used to extract biogas with greater methane concentrations used the coupled adsorption and absorption technique (Zhang et al. 2019). Powdered activated carbon and calcium hydroxide were the materials utilized in the experiment because of how reasonably priced they were. Calcium hydroxide was ground into a powder to increase the surface area. The calcium hydroxide was mixed with water, resulting in the formation of an aqueous solution of the substance. The initial calcium hydroxide flask was put to use in the process of extracting CO_2 from the raw biogas. To get rid of the H_2S, the biogas from the first flask was transferred into the second one using a connecting hose that contained powdered activated carbon.

RESULTS AND DISCUSSION

Physical and Chemical Characteristics of the Mixture of Substrates and Inoculum

The undigested and digested slurry was used to ascertain the physicochemical properties of the combined mixture of substrates and inoculum used for this experiment. The laboratory test findings, which were obtained at a temperature of 25°C and a humidity of 51%, explain the contents of the sludge before and after the anaerobic digestion process.

Carbohydrates, fat and protein: Large amounts of proteins and carbohydrates in the sludge may make it possible for more biogas to be produced during anaerobic digestion (Xu et al. 2018). Proteins and carbohydrates break down during the hydrolysis phase of digestion more quickly than lipids. Before digestion, the amount of carbohydrates in the sludge was higher than the amount of protein and fat, which helped to produce biogas. As shown in Fig. 4, hydrolysis, which lowered the quantity of the three macronutrients; carbohydrates, proteins, and lipids into smaller, more soluble molecules known as monomers, resulted in an average reduction of the three macronutrients by 45% after thirty (30) days of anaerobic digestion. As reported by Lohani (2020), this decrease in their contents shows that anaerobic co-digestion with eggshell added to control pH stabilized the digestion process inside the reactor and improved the biogas production due to the mixed feedstock's diverse composition.

Total solids (TS) and volatile solids (VS): After thirty days of anaerobic sludge retention time, there was a 25% reduction in the concentration of total solids (TS). Due to their ability to remove volatile solids (VS), which lowers the cost of pre-treating and dewatering digestate, the reactor's dry digestion phase with a considerable quantity of biogas generation is made possible by the percentage drop in total solids to 14.25% (Yi et al. 2014). The mixture of substrates and inoculum exhibited higher amounts of organic matter before and after digestion, as evidenced by the volatile solids (VS) content, with VS/TS ratios of 91.09% and 91.02%, respectively, as shown in Fig. 5. In the single- stage anaerobic bio-digester used in this research, biogas with increased methane (CH_4) concentration is produced due to quick stabilization during digestion when volatile solids (VS) are reduced during the anaerobic digestion process. The amount

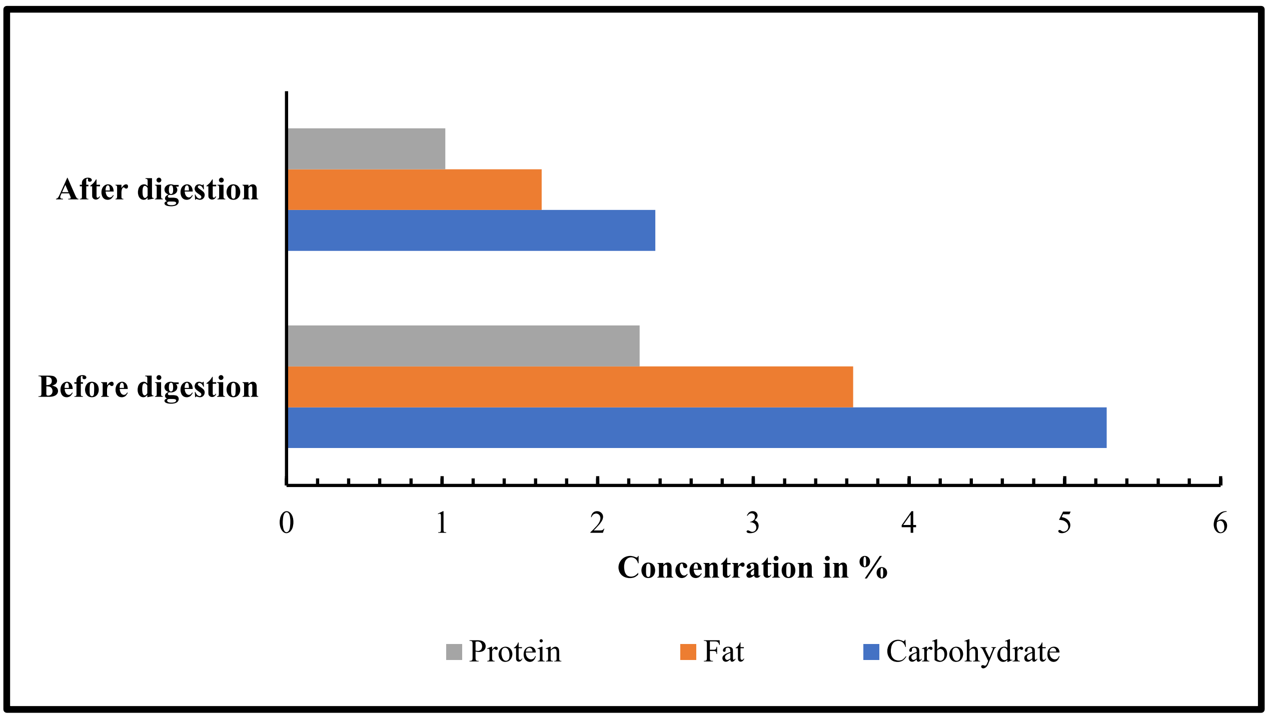

Fig. 4: Concentrations of carbohydrate, fat, and protein in slurry.

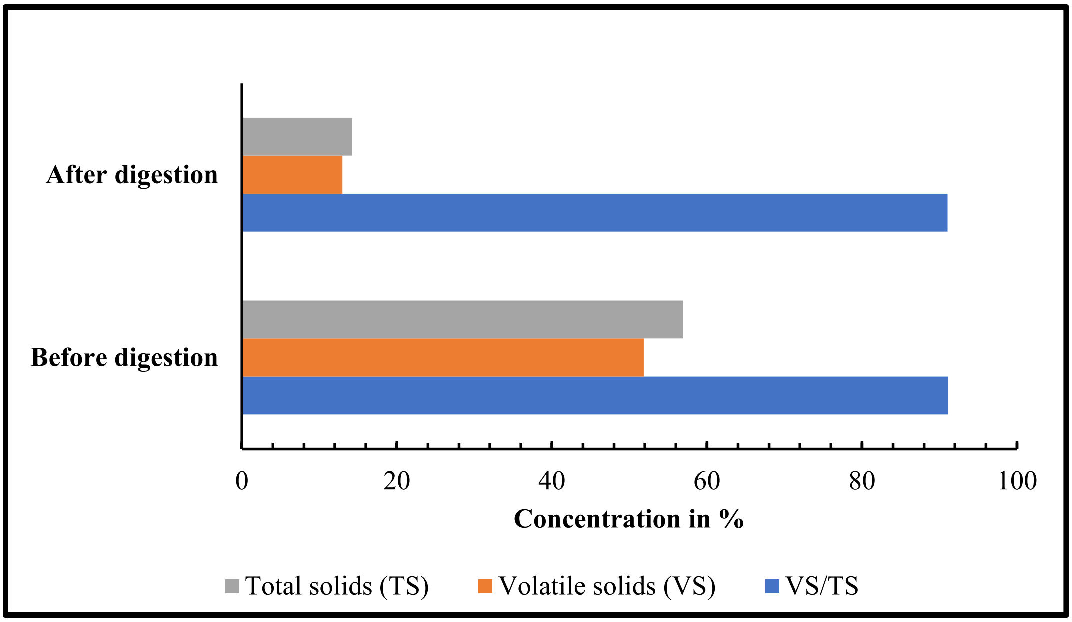

Fig. 5: Variation in the contents of total solids (TS) and volatile solids (VS).

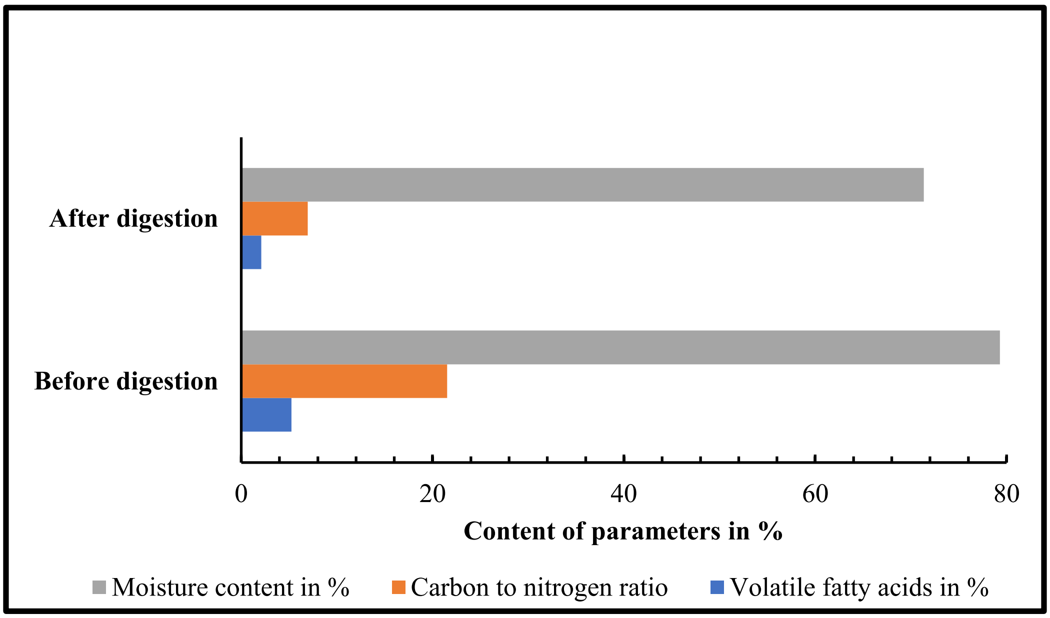

Fig. 6: Variation of volatile fatty acids (VFA), moisture content (MC), and carbon to nitrogen ratio (C:N) in the slurry.

of volatile solids (VS) in the slurry was reduced by 25% after 30 days of anaerobic digestion, with hydraulic retention time (HRT) being the deciding factor.

Volatile fatty acids (VFAs), moisture content (MC), and carbon-to-nitrogen ratio (C:N): Proteins in substrates degrade because the pH of slurry rises when the level of ammonia does, and it decreases when the amount of volatile fatty acids (VFA) increases (Kumar & Samadder, 2020). Volatile fatty acid (VFA) concentration dropped by 40% after digestion took thirty (30) days, which helped to maintain the pH to an average of 6.0 and sped up the breakdown procedure. As advised by Zhang et al. (2019), before digestion, the sludge's carbon to nitrogen (C:N) ratio was 21.53, which is in the range between 20 and 30. This

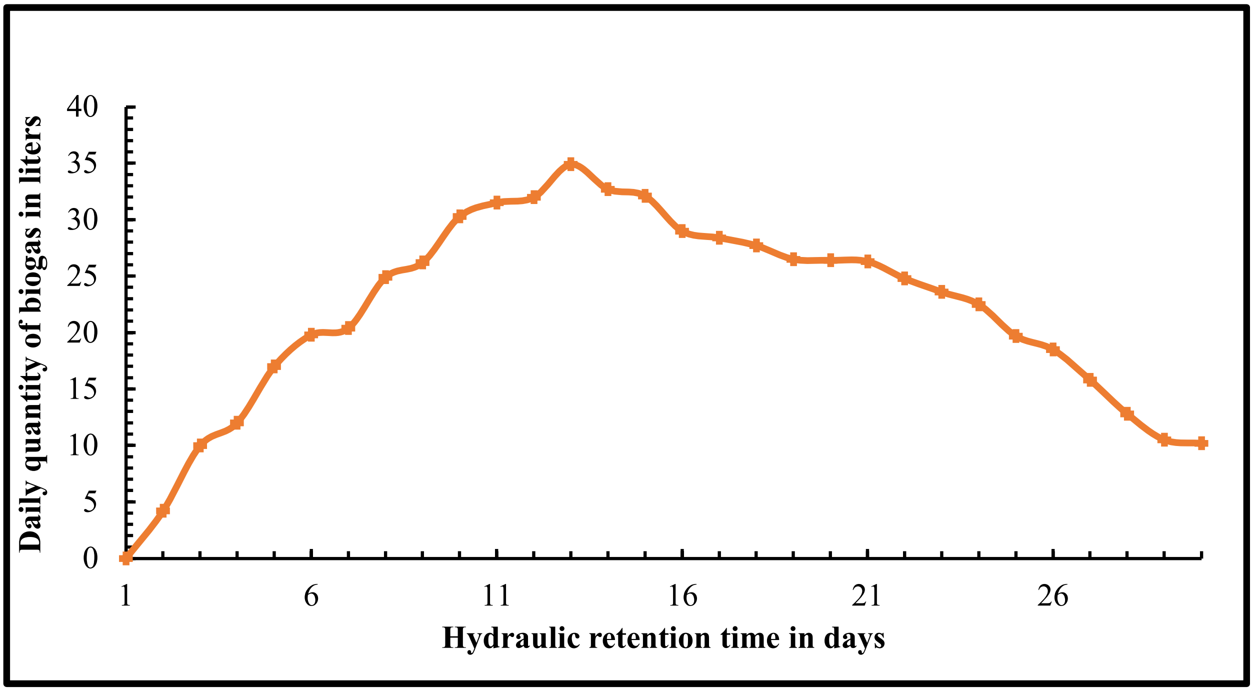

Fig. 7: Daily production of biogas from the anaerobic digester.

C:N ratio measurement demonstrated that the digestion method used to produce biogas was successful. Following the digestion process, the total carbon content decreased, and the C:N ratio subsequently exceeded the permissible threshold. In addition, the moisture level of 79.29%, as in Fig. 6, showed that there was room for microorganisms to move around freely and develop during the digestive process.

Generation of Biogas

The anaerobic co-digestion of cow dung, cassava peels, and palm oil sludge in this investigation resulted in a total of 650.6 liters of biogas from a 225L bio-digester, which is about 138% of the projected capacity in the design. More lignin content in palm oil sludge, which had a negative biogas contribution of roughly 34.24 percent, was a major factor in the inability to fulfill the predicted biogas for partial satisfaction of a single household. According to Fagbenle and Olukanni (2022), more biogas was produced through anaerobic co-digestion using cassava peels and cow dung as inoculum, both of which have high hemicellulose and low lignin concentrations. By successfully adjusting the pH using eggshells and the temperature to the mesophilic range using a greenhouse, a favorable habitat was established for the microorganisms that reacted with the sludge, increasing the production of biogas. According to Fig. 7, the maximum volume of biogas produced at the 13th day of retention time was 34.90 liters while that generated at the 20th day was 26.40 liters.

Fig. 8 shows the total volume of biogas generated by anaerobic digestion over the course of the hydraulic retention time, which was 30 days. The 225L PE digester used for the anaerobic co-digestion process started producing biogas in detectable levels on day two, at 4.20 liters. On day three, the biogas produced increased to 10.0 liters, and on day four, that amount grew to 12.0 liters. It was evident that the biogas generation had improved up to the 13th day of anaerobic digestion due to the favorable conditions for microorganisms generated by adding eggshells and a greenhouse for pH and temperature management, respectively. As in a comparable investigation carried out by Fagbenle & Olukanni (2022), the biogas was not created on the first day. The anaerobic co-digestion of cassava peels, palm oil sludge, and cow dung required a longer start-up time because of the oily content of palm oil sludge, which was also discovered by Aziz et al. (2020). The reactor's anaerobic digestion for 20 days of sludge retention revealed the best time that can be employed in batch digestion systems because the data indicate that biogas output started to decrease more after the 20th day.

pH Optimization and Biogas Generation

The pH value, which can be acidic when below 7.0 or alkaline when over 7.0, might affect how well the anaerobic digestion process works. The high acidity of the cassava peels and the palm oil sludge, both of which are similarly depicted by Fagbenle & Olukanni (2022), led to the sludge's

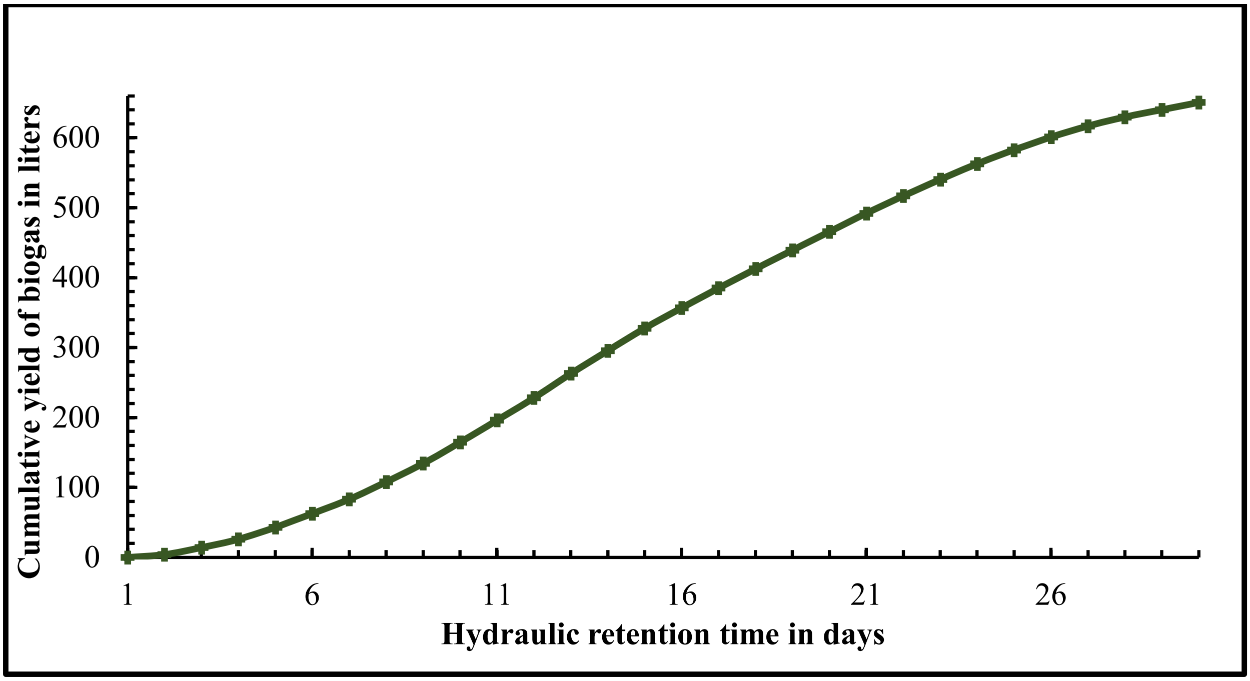

Fig. 8: Cumulative generation of biogas from the anaerobic digester.

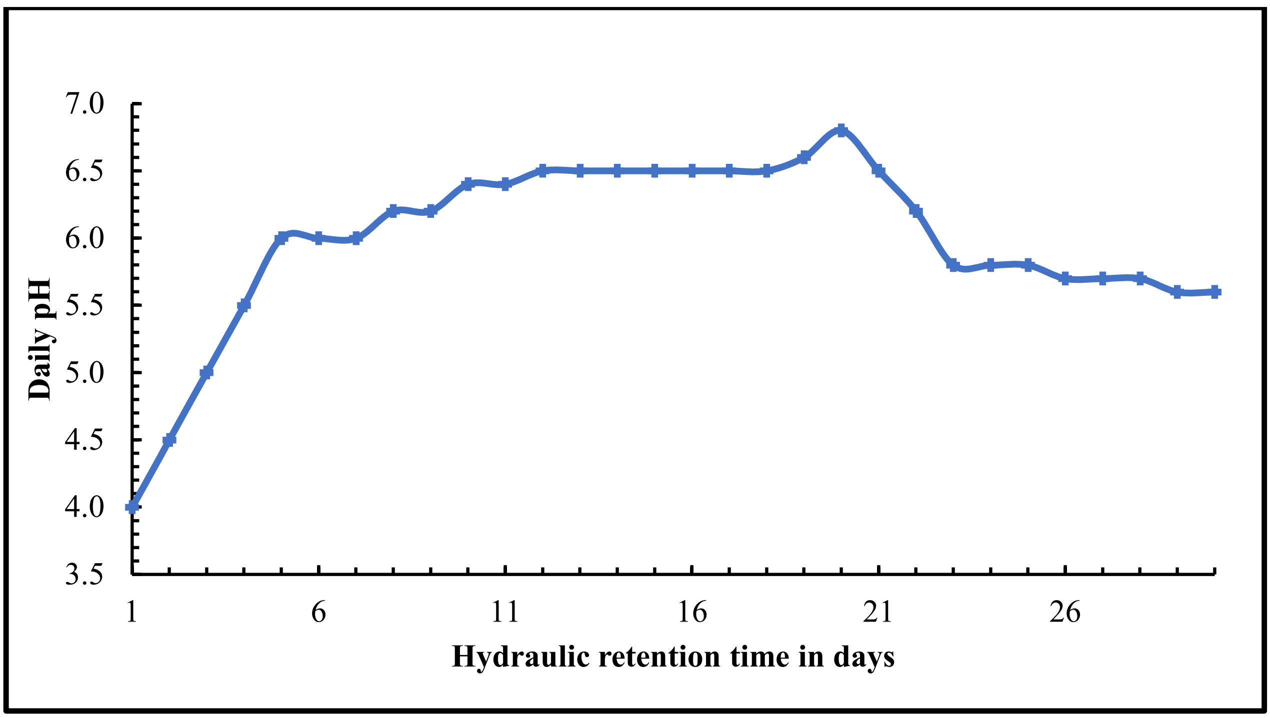

Fig. 9: Daily pH fluctuations.

pH value being high before digestion, as seen in Fig. 9. An average pH of 6.0 was found for the digestion period, which is within the range that is ideal for increased biogas since the microbial population may thrive in a hospitable environment, according to Zhang et al. (2019). The addition of green buffer material comprised of ground eggshells on the fifth day caused the pH value to begin rising toward the neutral range. On the thirteenth day, the digester system's biogas production reached its peak, with a pH value of 6.5 (within the ideal range of 6 and 8). The pH was able to be stabilized by the eggshells used as a buffer up to a value of 6.8, after which it returned to the acidic range and stayed there until the 30^{th} day of the anaerobic digestion process when it reached a value of 5.6.

Temperature Optimization and Generation of Biogas

The anaerobic co-digestion process was carried out inside a greenhouse that had been built to regulate the temperature. Daily measurements were made for the ambient, greenhouse, and slurry temperatures. An average slurry temperature of 34.76°C was found for the hydraulic retention period of 30 days, which is within the mesophilic range of between 30°C and 45°C, according to Zhang et al. (2019). While the surrounding air temperature was 28.18°C, the anaerobic digester's temperature was measured to have a mean of 33.58°C, which still fell within the mesophilic range. According to Oladejo et al. (2020), at mesophilic temperatures, anaerobic microorganisms function well to facilitate a mean catalytic efficiency of enzymes, enhancing the generation of biogas by stabilizing the AD process. The use of a greenhouse as a mesophilic refuge for an anaerobic digester has proven to be effective. The greenhouse that was built for the privacy of the digester during the anaerobic co-digestion process ensured the safety of the reactor against strong winds, heavy rain, and destructive objects. When the slurry temperature reached 35.83°C, which is ideal for mesophilic conditions, while it was 35.33°C in the greenhouse, 34.90 liters of biogas were produced at their highest rate. Fig. 10 depicts the average daily temperature for the ambient air, the greenhouse, and the reactor's slurry, respectively.

Components in Generated Biogas

As shown in Fig. 11, the amount of methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) in a sample of biogas produced by the reactor was measured after being collected and analyzed every ten days during the digestion period. The biogas is more combustible when there is more methane in it. The biogas produced in the first ten days had percentage concentrations of CH_4, CO_2, and H_2S that were out of the range recommended by Oladejo et al. (2020): 45.5, 51.5, and 3.5, respectively. As also observed by Oladejo et

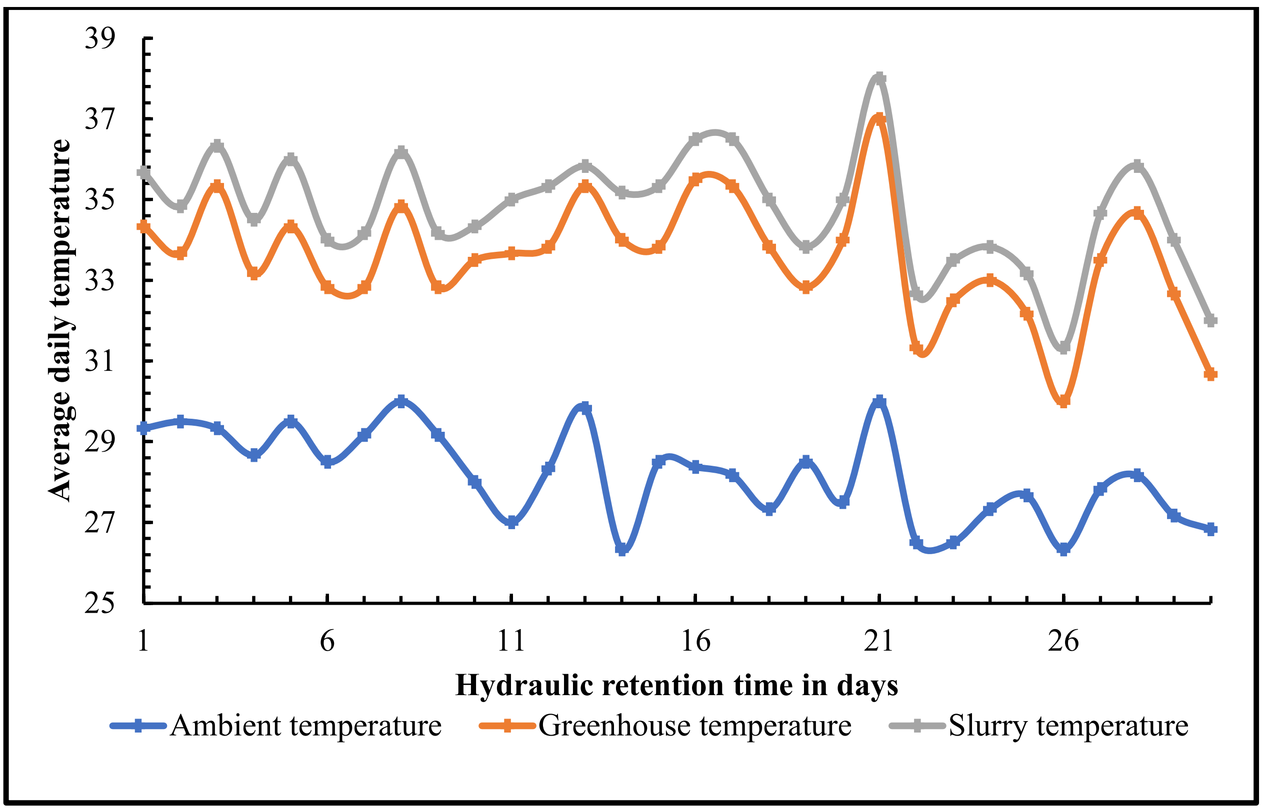

Fig. 10: Average daily ambient, greenhouse, and slurry temperatures.

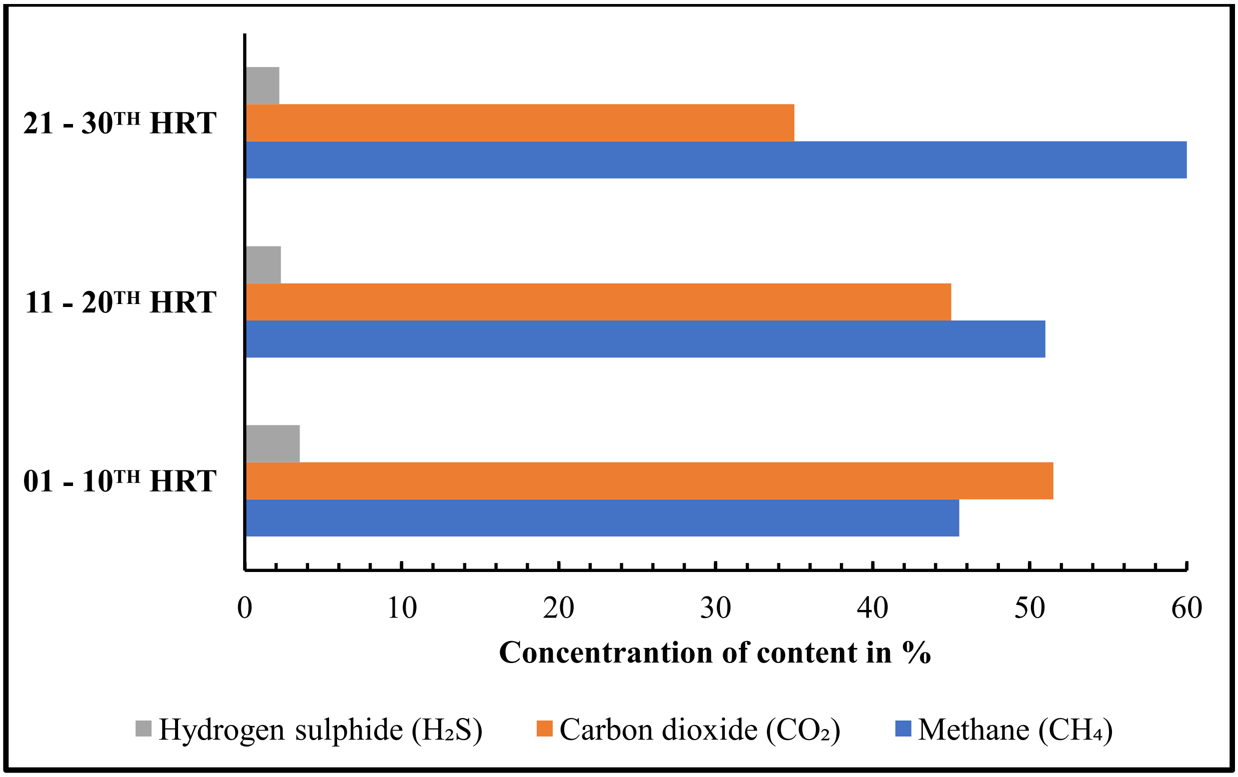

Fig. 11: Contents of the generated biogas

al. (2020), the concentration of methane (CH_4) grew to 51% in the second ten days, which is between 50% and 75%. The concentrations of CO_2 and H_2S reduced to 35% and 2.2%, respectively, over the third 10 days of the anaerobic co-digestion process, whereas CH_4 content increased to 60%. The amount of methane (CH_4) found through testing in laboratories from hydraulic retention durations of 20 days to 30 days showed that the biogas is combustible when it catches fire and can be utilized for cooking and lighting in homes.

Purification of Biogas

The removal of pollutants, including carbon dioxide (CO_2) and hydrogen sulfide (H_2S), was undertaken to produce biogas high in methane (CH_4). An efficiency of around 92% was achieved in removing CO_2 contamination, which was higher than other contaminants from the biogas produced. This elimination efficiency was also noted in the research mentioned by Fagbenle & Olukanni (2022). After 240 minutes of the absorption process, employing an aqueous solution of calcium hydroxide ($Ca(OH)_2$), the CO_2 extracted from the created biogas was finally stripped into liquid condition. As shown in Fig. 12, there was only a very tiny variation in the amount of CO_2 that had been lowered between 180 minutes and 240 minutes, with the difference being less than or equal to 4.7%.

However, it was discovered that the efficacy of the reduction in hydrogen sulfide (H_2S) concentration was around 85%. For biogas to be used in engine combustion, Fagbenle & Olukanni (2022) states that the H_2S concentration in the gas cannot be more than 0.5%. As demonstrated in Fig. 13, after a single-phase treatment with activated carbon for 240 minutes, the amount of H_2S in the produced biogas was reduced to 0.39 percent, making it appropriate for engine combustion. According to Oladejo et al. (2020), the final output of treated biogas has a concentration of less than 3%, which permits the storage of purified biogas in storage tanks without producing corrosion for household uses like cooking and lighting.

CONCLUSION

The findings of this study demonstrate that the anaerobic co-digestion of ground eggshells, cow manure, cassava peels, and palm oil sludge is a feasible and environmentally beneficial approach for obtaining energy in the form of biogas. A pH level that is within the range advised for the anaerobic digestion process was maintained in the mixture of

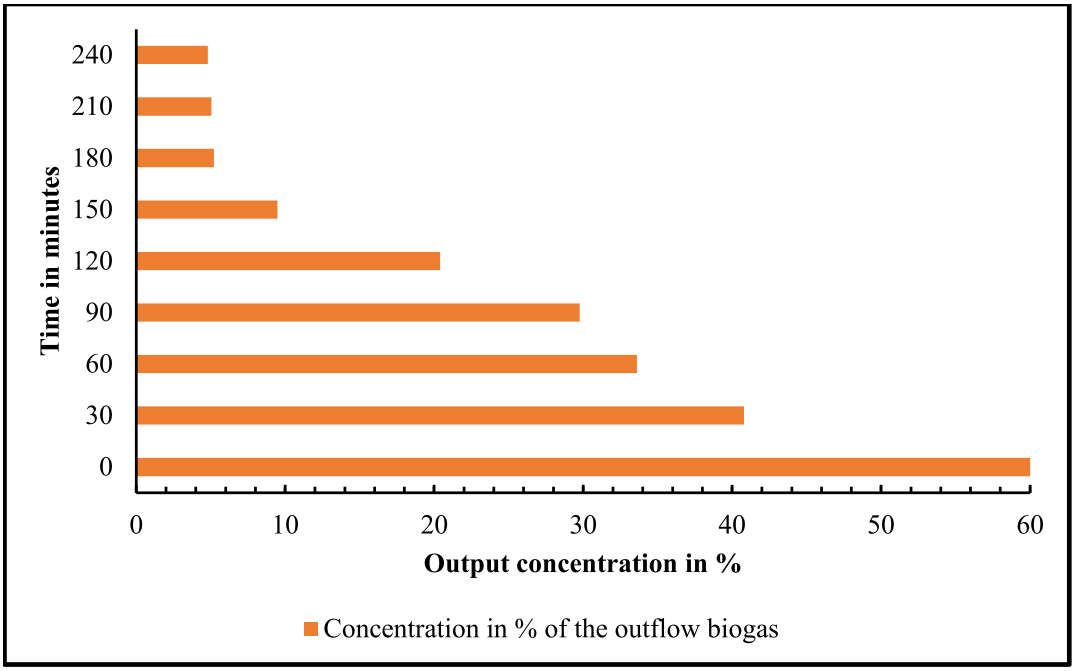

Fig. 12: Concentration of output biogas during CO_2 removal.

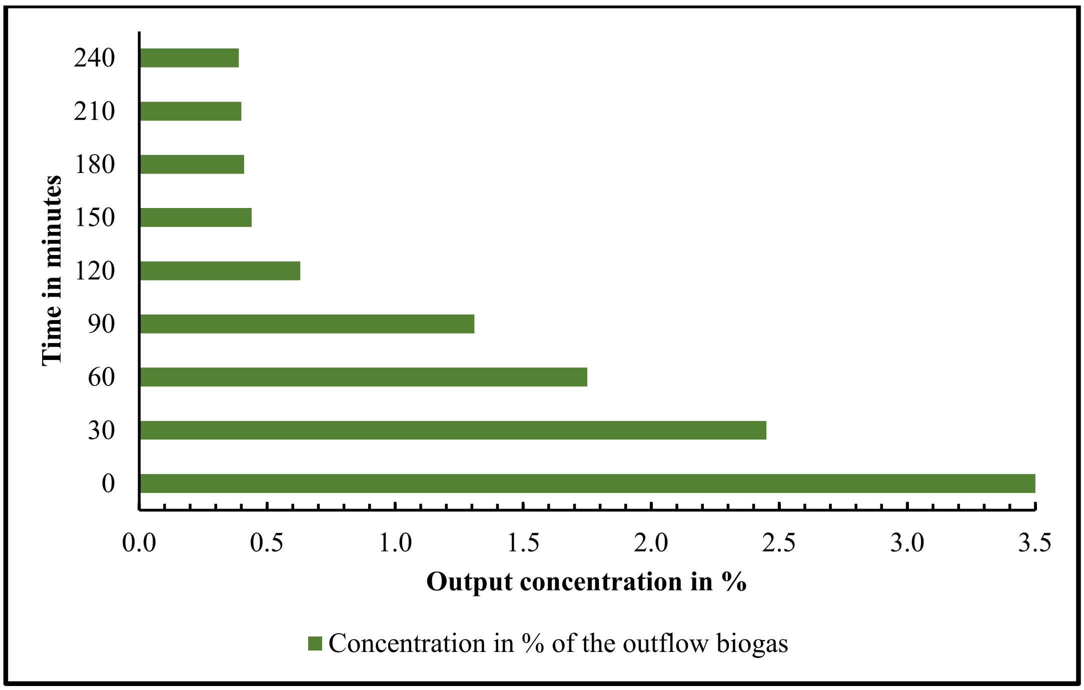

Fig. 13: Concentration of output biogas during H_2S removal.

substrates and inoculum with powdered eggshells added as a buffer material. The use of greenhouses to adjust temperature has shown to be a viable method for maintaining mesophilic conditions during anaerobic co-digestion for increased biogas production. The 225L digester used for the anaerobic co-digestion process produced 650.60L of cumulative biogas for the 30-day sludge retention period. From the biogas produced on days over 20 HRT, the greatest methane concentration of 60% was found, while on days under 10 HRT, the lowest methane content of 45.5%. On the 13th day of anaerobic digestion, the production of biogas reached its peak at 34.90L, while pH and temperature were kept at optimal levels for a healthy anaerobic digestion process with 6.5 and 35.83°C, respectively, on that same day. With an efficiency of 92% and 85% for the removal of CO_2 and H_2S, respectively, the purification strategy using combined absorption and adsorption has shown to be a successful way of treating biogas produced in 20 days or more of hydraulic retention time. Future research should focus on the discovery and development of more effective, less expensive microbial agents, such as enzymes for biological pre-treatment and more environmentally friendly chemical solvents for chemical pre-treatment of palm oil sludge, to reduce a significant amount of lignin that has a negative impact on biogas generation.

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