Optimising Biogas Production from Anaerobic Co-Digestion of Chicken Manure and Organic Fraction of Municipal Solid Waste

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Abstract— **In this study, it was observed that in experimental work under laboratory scale using conventional biochemical methane potential (BMP) assay, the loading rate ratio 4:1 had optimum biodegradability rate than other ratios which were investigated, while the loading rate ratio of 1:1 had optimum biogas and methane yield after 15 days hydraulic retention time. It was concluded that chicken waste (CM) mono-digestion has higher biodegradability rate compare to organic fraction municipality solid waste (OFMSW) mono-digestion. Co-digestion of OFMSW and CM stabilizes conditions in digestion process such as carbon to nitrogen (C:N) ratio in the substrate mixtures as well as macro and micronutrients, pH, inhibitors or toxic compounds, dry matter and thus increasing biogas production. It was concluded that the organic waste generated in the municipal landfills could be co-digested with CM to produce methane which can be used as a source of environmentally friendly and clean energy for the transport sector, industries and residential homes.**

Keywords **–** Anaerobic, biogas, co-digestion, micronutrients, mono-digestion, OFMSW.

I. INTRODUCTION

THE economics development of African countries depends on power generation and use. With the fast depletion of non-renewable energy sources such as coal and fossil fuel which has led to environmental degradation, human health problems and global climate change [1, 2]. The commercial production of bioenergy and other alternative energy sources such as solar energy, wind energy, hydropower, geothermal will definitely give a drive for the development of the economy [1-3]. Energy efficiency is dependent on the thermal insulation properties, quality and structure of the construction. The continuous in prices for heating, electricity and operational expenses gives increased interest in the use of renewable energy sources and development of energy efficiency methods (models). It important not only to be able to produce cheap and clean renewable source but also to take into account the climate change and optimize the use [4]. According to Esen, M., et al. [5] the interest in an alternative or renewable energy sources for greenhouse heating is currently high, due to relatively high prices of fossil fuels and heating loading. This gives alternative sources of energy like biogas, solar, and ground sources heat pump greenhouse heating systems (BSGSHPGHS). These study demonstrated that some renewable energy source such as biogas, solar and ground energy can efficiently heat greenhouses during winter [5]. According to Cuce, E., et al. [6] on the analysis of total energy consumption; energy efficient are environmentally friendly technologies. Renewable energy technologies are widely considered to reduce world energy consumption that dominates fossil fuels and mitigate greenhouse gas emissions in the atmosphere through clean energy generation. This reduces operational costs and ultimately carbon emissions. Thus, reducing the dependency of the grids [6]. According to Behera, B., et al. [7] on the study of factors determining the household use of clean and renewable energy sources for lighting in Sub-Saharan Africa using data from Living Standards Measurements Study (LSMS). Its shows people who still live in the rural area depend on kerosene, solid fuel, batteries for lighting while a just small fraction of the population uses renewable energy such as solar, bioenergy [7]. Renewable energy system such as solar photovoltaic, solar thermal, geothermal and wind technologies are currently used in water treatment such as desalination systems according to Al-Karaghouli, A., et al. [8]. Energy cost, maintenance cost, capital investment and operational cost are the main contributors to the water production process. Energy cost contributes 50% of the water production cost. Using renewable energy sources assists in lowering the energy cost and at the same time saving the environment [8]. The objective of the study was to look into the benefits and pitfalls encountered when co-digestion is employed while selecting a high yield co-digesting substrate for use in an anaerobic digester. The study focused on the following objectives:

1 Determine the effect of mono-digestion and co-digestion of CM and OFMSW on biogas and methane production in an anaerobic digester.

2 Optimize the efficiency of biogas and methane production of CM and OFMSW by looking into process parameters such as; organic loading rate (ratios).

1. Biogas Production

Biogas is used in the form of fuel, heat and electricity. It is desirable to create a worldwide energy friendly system which is sustainable and with zero carbon emissions. This results in resource conservation and environmental

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protection [9, 10]. In cogeneration units (combined heat and power (CHP) biogas which is dried and sulphur free can be used to produce heat and electricity [11]. It can be further upgraded to biomethane by concentrating methane in biogas. This is achieved by washing with water, membrane separation technology, amine gas treating, pressure swing adsorption and selexol adsorption to remove the CO_2 and H_2S in biogas. Bio-methane retains similar characteristics as natural gas. Therefore, it can be used in gas engines and vehicle fuels since it can be stored the same way as natural gases. As more applications of biogas are being discovered, it can also be used to substitute carbon in plastic production. In Europe and its state of the Soviet Union, it has been estimated that bio-methane production by the year 2020 they will achieve 250 billion standard cubic meters (m^3N) of bio-methane which will be sufficient to cover half of the current consumption. Biogas is produced in an anaerobic digester using mono-digestion or co-digestion. Co-digestion favours high yield of methane due to the availability of varies vital trace elements contributed by the different substrate. In mono-digestion, these essential trace elements are insufficient [11].

Biogas is composed of gases such as methane, carbon dioxide, hydrogen, carbon monoxide, hydrogen sulphide, ammonia and a trace amount of oxygen. It is produced by the breakdown of biodegradable organic materials using bacteria under controlled conditions. These include municipal solid waste, agricultural waste, industrial waste and animal waste [12, 13]. When the process is operated at optimum conditions the ratio of CH_4 to CO_2 is approximate 60:40 [14]. Biogas is a source of bioenergy. In satisfactory amount and standard can be utilised for electricity or heating [14]. In combustion, methane is converted into bioenergy, therefore, it is not released to the surroundings. However, CO_2 is released in small amounts that do not affect the atmosphere compare to that of CH_4 and nitrous oxide N_2O when they are in the atmosphere [14]. In a case where CH_4 and N_2O are in the atmosphere, they have a great impact due to their greater ability to trap energy compared to CO_2 [14].

Biogas production takes place in series of four biochemical fundamentals steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis [15]. Figure 1 shows biochemical steps of the anaerobic digestion process. Hydrolysis is the first step of the biogas decomposition process. This step involves the breaking down of large organic polymer chain into smaller molecules.

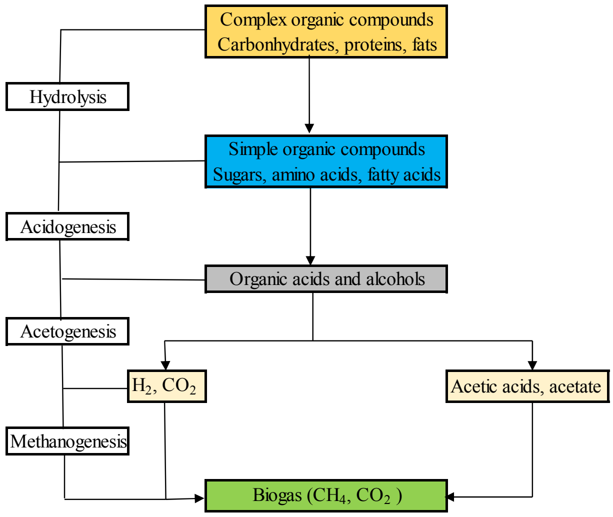

Figure I: Biochemical steps of anaerobic digestion process [16, 17].

During this phase, carbohydrates are broken down into simple sugars, protein into amino acids and fats into long fatty acids [18]. While some of the products of hydrolysis including acetate and hydrogen may be used by methanogens in the last stage in the anaerobic digestion (AD) process [19]. The products of hydrolysis then undergo the next step in AD known as acidogenesis in which acidogenic microorganisms further break down the substrates. These fermentative bacteria produce an acidic environment in the digestion media while creating ammonia (NH_3), hydrogen (H_2), carbon dioxide (CO_2), hydrogen sulphide (H_2S), shorter volatile fatty acids, organic acid (acetic, butyric acid, propionic acid, lactic acid etc.), and low alcohols are produced [19]. During acetogenesis step, a derivative of acetic acid known as acetate is created from carbon and energy sources by acetogens. This is a very important step in the AD that requires close cooperation between the organisms that carry out oxidation and the methane-producing organisms that are active in the next stage of actual formation of methane [18]. This process constantly utilizes hydrogen gas thus keeping the concentration of hydrogen gas at a sufficiently low level. Methanogenesis is the final stage of AD in which methanogens create methane from the final products of acetogenesis (i.e. carbon dioxide, hydrogen gas and acetate) as well as from some of the intermediate products from hydrolysis and acidogenesis [20]. In this stage, carbon dioxide and methane (biogas) are formed by various methane-producing microorganisms called methanogens [16, 18, 19]. Equation 1 shows a simplified generic anaerobic digestion [21].

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \quad (1)$$

A. Conditions of Anaerobic Digestion

The rate of biogas production depends on a number of conditions (parameters) that include; hydraulic retention time, temperature, C/N ratio, organic loading rate, partial pressure, pH, nature of the substrate, microbes balance, and Oxygen exposure to anaerobic [22-25].

1.1 Temperature

To operate at the optimum temperature, it is important to consider the type of microorganism present and the conditions they survive in. Microorganisms are classified in terms of the temperature range in which their growth accelerates [26]. Temperature classification of the microorganisms is psychrophilic, mesophilic and thermophilic.

- Psychrophilic optimum operating temperature range is <10 ºC.
- Mesophilic is within 20-45 ºC and optimum temperature is 35 ºC.
- Thermophilic optimum temperature is >50 ºC, normally the operating optimum temperature range is 55 ºC. An anaerobic digester operating at thermophilic condition is mostly unstable and has high energy intake although it produces a high percent of the biogas.

1.2 pH

The AD process is greatly affected by variation in levels of pH. Microbes cannot grow under high acidic conditions, hence anaerobic digester failure or low methane yield occurs. Optimization of digestion pH is preferred to be ranging from 6 to 7 [27, 28]. The first stage produces volatile fatty acids which lower the pH due to the chemical interaction of CO_2 and water (H_2O). Hydrogen carbonate ions are formed and restore stability. See equation 2 and 3.

$$CO_2 + H_2O = H_2CO^{3-} = H^+ + HCO^{3-} \qquad (2)$$

$$H_2CO^{3+} + OH^- = HCO^{3-} + H_2O \qquad (3)$$

It is recommended to maintain alkalinity at roughly a 3000 mg/L for optimizing methane yield [26].

1.3 Retention Time

Retention time is the period taken by biodegradable material and microorganisms in the anaerobic digester to reach depletion [29]. The retention time depends on the substrate composition, temperature, digestion system classification as well as the processes. Retention time in mesophilic anaerobic digester conditions normally is within 15 to 40 days. While for thermophilic anaerobic digester retention time is within 12 to 14 days [29]. Solids retention time (SRT) is the period taken by living microorganisms located in the AD process. The HRT and SRT have a relationship with the importance of 'Food to Microorganism ratio' (F/M) [29]. The digester can be operated at a mesophilic or thermophilic condition, but the microorganisms will have a limited amount they can feed on per day. Therefore, to operate within targeted retention time, digestion system should be supplied with a sufficient number of microorganisms [29].

Food to microorganism's ratio can be defined as the ratio of the measure of feedstock and to the measure of microorganisms existing to ingest that feedstock. This ratio finds its application in all biological treatment processes. SRT is maintained at a high level in order for the F/M ratio to remain minimised. In this case, digester efficiency is enhanced to increase production of biogas [29].

1.4 Loading Rate

To optimise the loading rate in the anaerobic digester, it is important to know the biodegradable material content such as dry solids and volatile contents [29]. Loading rate is inversely proportional to methane production. In an anaerobic digester, an increase in the substrate than bacteria results to the bacteria being unable to decompose this substrate. This is caused by the accumulation of undigested biodegradable material such as fatty acids. This creates an acidic environment which decreases the pH and results in unstable decomposition process [29].

1.5 Mixing/agitation

The operating conditions, substrate concentration and temperature are kept uniform when mixing is adopted. Mixing also minimizes solids build up and the occurrence of scum [29].

1.6 Carbon Nitrogen Ratio (C:N Ratio)

The feed at C: N ratio of 30:1 results in optimum methane yield. C: N ratio determines the occurrence of digestion [17, 29]. As carbon creates the energy source for the microorganisms, nitrogen results in the formation of ammonia gas. When the levels of C: N ratio is high, there is fast depletion of nitrogen (N) used by bacteria that produce methane, to satisfy their protein needs, therefore, resulting to less biogas production. When pH level is greater than 8.5 promotes a toxic environment for the methanogenic bacteria to exist. To operate the anaerobic digester at optimum C:N ratio, biodegradable material of high C: N ratio should be blended with the biodegradable material of low C: N ratio. Table 1 shows the C/N ratio of some biodegradable materials [29].

Table I: Biodegradable material C/N ratio

C/N ratio of some biodegradable materials

Raw material	C/N Ratio
Duck dung	8
Human excreta	8
Chicken dung	10
Goat dung	12
Pig dung	18
Sheep dung	19
Cow dung	24
Water hyacinth	25
Municipal solid waste	40
Elephant dung	43

Maize straw	60
Rice straw	70
Wheat straw	90

The optimum conditions for the C/N ratio must be within 15 to 30:1[30]. However, micro-organisms must have a 20-30: 1 ratio of C/N [31]. Carbon is consumed at a faster rate; therefore, a high percentage is required to operate at maximum conditions.

1.7 Moisture Content

Water is important for the bacteria in the digestion process to live longer. It is due to moisture content for the bacteria to release biogas and occurrence of metabolic processes [31]. Hence, moisture is significant for optimal digestion as it aids the digestion process to yield high-quality biogas rich in CH_4. The literature recommends that the moisture content for optimum conditions to be 90%. However, an increase in the moisture content could lead to digestion process failure [31].

1.8 Concentration of feedstock

The concentration of feedstock is defined in terms of solid concentration which is the measure of biodegradable materials in unit volume slurry [31]. The rate of digestion depends on the concentration of the feedstock. An increase in solids concentration may result to poor biogas production. At low-temperature, digestion will take a longer period [31].

1.9 Chemical Oxygen Demand (COD)

In the anaerobic digestion, COD is normally taken as a control tool for anaerobic systems. COD is used to determine the organic material content of feedstock sample. This is achieved by introducing a strong biochemical reacting agent to the feedstock in an acidic system [32]. Operating an anaerobic reactor using COD balance serves as a tool to monitor digester performance and this gives vital information about the efficiency of the anaerobic process [33]. Figure 2 shows COD balance of an anaerobic digestion

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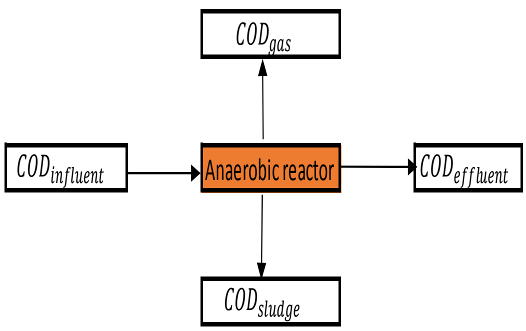

Figure 2: COD balance of an anaerobic digestion

1.10 Organic Loading Rate (OLR)

This parameter indicates the quantity of biodegradable material fed to an AD within a given period normally presented as capacity per day [32].

1.11 Substrate Pre-treatment

Pre-treatment is done to increase the efficiency of AD technology and increase the production of biogas [34]. Pre-treatment can be classified as mechanical, thermal, biochemical pre-treatment. It is necessary since the nature of a substrate has an effect on the biogas production rate [34].

1.11.1 Mechanical Pre-treatment

Mechanical pre-treatment is the reduction of the particle size resulting to increased specific surface area [34]. AD process efficiency increase due to a large area being exposed to the bacteria. When the specific surface area is not exposed, the chemical oxygen demand degradation is lowered as well as the methane production. The studies show that the relationship that exists between particle size and production rate of biogas is inversely proportional [34]. The size reduction in the mechanical pre-treatment process can be achieved by the following equipment:

- Lysis-centrifugal
- Liquid shear
- Collision high pressure
- Homogeniser
- Macerator

When optimising the AD, it is ideal to reduce the size of the substrate in order to make it easier for bacteria to break down the substrate and prevent clogging of the digester [34]. Sharma et al, [35] found that substrate with a size of 0.088 mm and 0.40 mm is ideal for optimised production of biogas as compared to 1.0, 6.0 and 30.0 mm particle size. Mechanical pre-treatment has a benefit of reducing the volume of the digester required without affecting biogas production rate [34].

1.11.2 Thermal Pre-treatment

Thermal pre-treatment is also known as liquid hot water. It involves heating feedstock at 220 ºC for a given pressure [34]. However, before feeding the feedstock, it is cooled to a lower temperature. Thermal pre-treatment has the following benefit:

- Leads to pathogen removal
- Improve dewatering performance
- Reduce viscosity of the digestate, hence making it easier to handle digestate

However, it can result in loss of volatile organics then lower bio-methane production from an easily biodegradable substrate. Therefore, the effect of thermal pre-treatment depends on the biodegradable material and mesophilic and thermophilic conditions [34].

1.11.3 Chemical Treatment

Chemical pre-treatment is applicable in the removal of the biodegradable material by using alkalis, strong acids in a digestion process. In case pH needs to be adjusted in the digestion process by raising alkalinity, therefore alkali pre-treatment will be used. Alkali pre-treatment increases the specific surface area. An increase in the specific surface area means the microbes in the anaerobic digester can easily reach organic material in the substrate. Acid pre-treatments or oxidative methods are used to enhance digestibility and hydrolysis rate of lignocelluloses materials. When hydrolytic enzymes reach hemicellulose, they break down the lignin and remove acetate group. There will condense lignin and eventually it will precipitate [34].

1.11.4 Biological Pre-treatment

This process is for microbiological pre-treatment, pre-acidification and multi-stage fermentation [34]. The process separates the first two stages in AD which are hydrolysis and acidogenesis from other two stages which are acetogenesis and methanogenesis. In the first digester, pre-acidification is adopted and pH is maintained between 4 and 6, resulting in methane production being inhibited due to the build-up of volatile fatty acids (VFAs). In this case, hydrolytic enzymes efficiency is at maximum resulting to the formation of H_2 due to lower pH levels as the substrate decomposes [36].

1.12 Co-digestion

Studies show that co-digestion is a way of improving methane production and minimising HRT [28]. Co-digestion of feedstock, biomass waste can produce more methane than manure, but the challenge in this process is to achieve completely break down of organic material in hydrolysis. The retention time can take over 100 days [28]. The importance of co-digestion is to stabilize conditions in digestion process such as C: N content as well as macro and micronutrients, pH, inhibitors or contaminated compounds and dry material [28]. The economic and ecological advantages of co-digestion of manures and organic fraction of municipal solid waste include:

- Better handling of mixed waste as a slurry this makes it easy for transportation since it can be transported via pipes and slurry occupy less space when compare to a solid waste.
- Enhanced productivity of AD by blending manure and biomass waste and this offers a high possibility of energy production in rural areas.
- In the rural area, it maximises the capacity of obtainable feedstock for each household because of the inadequate quantity of waste from a particular home.
- Cost effective and better technique to optimise AD productivity.
- It increases the nutrients and bacterial variety in substrate hence optimises the AD
- Minimise retention time hence maximise the efficiency of biogas production due to a variety of organic material contributing to good nutrients for the bacteria in an anaerobic digester.
- The best way of managing waste is the use of manure in AD minimise land and air pollution.

1.13Purification of Biogas

The purification of biogas is mainly done for the following reasons:

- To remove harmful components trace. Hence protecting natural gas grid and appliances
- Enrich methane

Upgraded methane is called bio-methane which consist of 95 to 97 % CH_4 and 1 to 3 % CO_2. Biomethane can be used as an alternative for natural compressed gases [37].

Water is removed by varying the parameter that will condense it [37]. This could be lowering temperature or increasing pressure. The removal of water is done to prevent the occurrence of corrosion by making sure that the water in the system does not come into contact with compressors, pipes, activated carbon beds and other parts of the process. The removal of H_2O also forms part of biogas purification. Hence, water is removed by adopting adsorption or absorption methods at reasonable maximum pressure [37].

Table 2: Biogas contaminations and their consequences

Impurity	Possible Impact
H_2S	Deterioration in compressors, gas storage containers and engines. Contaminated concentrations of H_2S (> 5 cm^3m^{-3}) remain in the biogas. SO_2 and SO_3 are formed due to incineration, which is more toxic than H_2S and causes rusting in the presence of water
CO_2	Small calorific assessment
Siloxanes	Formation of SiO_2 and microcrystalline quartz due to incineration
Hydrocarbons	Deterioration in engines due to combustion
NH_3	Rust when dissolved in water
O_2	Volatile material due to great concentrations of O_2 in biogas
Cl_2	Rust in combustion engines

1.14 Digestate

Digestate is a by-product in the production of biogas in anaerobic digester [38]. Digestate composition depends on the type of biodegradable material for the digestion process. It is composed of nitrogen, phosphorus and potassium (NPK) and other traces such as; calcium (Ca), magnesium (Mg) and sulphur (S). It can be used as a bio-fertiliser (organic fertilizer) and soil improver to eliminate the use of mineral fertilisers [38]. The advantages of using digestate as a fertiliser includes:

- High nutrient content (NPK) compared to untreated organic waste.
- It introduces essentially micro-nutrients that were not biodegradable during digestion process for plants and microbial growth
- Reduce odour by replacing the use of untreated manure as a fertiliser
- Suitable for improving soil conditions (landscaping) due to the application of organic matter
- In large production digestate value can be enhanced and be introduced to new market
- Improved veterinary safety
- Pathogen reduction

1.15 Previous studies findings

Zhu, H., et al [39] investigated the production of CH_4 from CM at varied organic loading rates (OLRs) and in a mesophilic acidogenic to thermophilic methanogenic two-stage digestion processes. In the acidogenic reactor (RA), the biogas produced had 30% to 45% CH_4 content. In the methanogenic reactor (RM) the biogas produced was significantly high within the range of 75% to 85% CH_4 content and a mean of 79%. Therefore, at different OLRs in a mesophilic RA to thermophilic RM two-stage process with an average of 74% CH_4 content was achievable. This was in the same range with the study that was done by Mojapelo, N., et al. [40] which obtained 73.5% CH_4 content. Li, Y. et al. [41] found a value within the range of 70.5 to 76% while Hansen, K.H., et al. [42] found a value of 76% CH_4 content. It was concluded that biogas production for CM used as a substrate with total solids (TS) loadings greater than 5% can be optimised by using a two-stage mesophilic acidogenic to thermophilic methanogenic. This was achieved independently of additives to control pH and the other substrate was not rich in carbon (C). The HRT took 12 days with TS values in the range of 3 to 8.25 %.

A previous investigation was conducted Mojapelo, N., at al [40]. The key objective of the study was to determine biomethane potential (BMP), quantification and characterization of OFMSW. Bio-methane potential (BMP) of the OFMSW was determined using a four bench-scale anaerobic batch digesters operated at optimum pH and temperature which were 7 to 7.5 and 35 ^oC respectively in an automatic water bath. The volume of CH_4 was measured on a daily basis using the downward water displacement in the 2 litre measuring cylinders. The studies show that the moisture content (72.86 %) was within the recommend range for digestion. The C/N ratio was also within a suitable range for MSW of 25:1. The production of biogas for OFMSW in four digesters used took 14 days. Biogas produced was 0.385 l/gVS which is in agreement with 0.4l/gVS that was obtained by Kubaska, M., et al [43]. The production of biogas was achieved at a high rate on the first days. This is due to the high-fat content in OFMSW.

The production of biogas was also enhanced by seeding and agitation. This study for OFMSW achieved average content of CH_4 to be 62% while CO_2 was 38%. The studies report that OFMSW has a potential to produce biogas that has 58 to 70% methane. Wu, L. [44] reported that biogas production from the bio-waste is in the range of 0.3 to 1.0 m^3/kg oDM.

Jorgensen, P.J. [45] carried out an investigation to evaluate the proper ratios of Corn Stover (CS) and chicken manure (CM) in order to optimise biogas production using BMP analysis. The investigation was also intended to determine CH_4 yield, volumetric CH_4 productivity and AD stability during the digestion of CS, CM and when they are in co-digestion. The slurry from wastewater treatment plant was used as the inoculum. The production of biogas for co-digestion of CS with CM after 16 days was 90% methane. However, the AD of CS and CM separate was 55.4% and 64.8% CH_4 content respectively. Earlier studies show that the digestion process of CS and CM separate was 45.0% and 47.0% CH_4 content respectively [46]. The differences between the results obtained from the studies are due to using different mixture content of substrate and inoculum. In terms of VS the ratio of 3:1 and 1:1 for CS and CM has high biodegradability percentage compared to mono-digestion of CS and CM. The rise in the biodegradability of the substrate may be due to the change in C: N ratio. In mono-digestion the C: N ratio is 63.2 and 10.1 for CS and CM respectively, while in co-digestion of CS and CM with BMP ratio of 1:1 and 3:1 the C/N ratios are 17.4 and 27.3 respectively.

Sreekrishnan, T.R., et al. [21] recommends that for optimum conditions the C/N ratio must be within 15 to 30. Hence co-digestion of CS and CM with BMP ratios of 1:1 and 3:1 and pH of 7.1 and 7 respectively result to optimum biogas production.

The main objective of this study was to optimize production efficiency of biogas by investigating the effect of co-digestion of chicken manure (CM) and organic fraction of municipal solid waste (OFMSW) on biogas production in an anaerobic digester. To optimize biogas production of this substrate, the focus was given at organic loading rate and co-digestion of the substrates.

II. METHODOLOGY

2.1 Substrate quantification

Quantification is a process that enhances substrate quality. The OFMSW were collected from Robinson landfill in Johannesburg, South Africa. Before analysis, CM sample was passed through a 2 mm and 1mm sieve to remove large particles such as eggs shell, feathers, stones and other unwanted materials. 50 g sample of the bulk sample was used to perform tests. The OFMSW and CM samples obtained from the quantification process were kept in plastic bags free from air. These samples were kept in a fridge at 4°C for further tests.

2.2 Substrate characterization

Waste characterization was done to ascertain the composition. These included physical and chemical composition with regards to C/N ratio, volatile solids, total solids and elemental analysis for carbon, nitrogen, sulphur and hydrogen in accordance with the standard method (APHA 1995) [47].

2.3 Biogas Production

The analysis was experimentally achieved on a laboratory scale using automatic methane potential test system (AMPTS II). In this system biochemical methane potential (BMP) tests were performed to determine the anaerobic biodegradability and optimum methane potential of waste as well as the biodegradation rate on a laboratory scale. The digesters were marked and filled with inoculum and substrate. The rubber stoppers were lubricated with silicone spray on the side that is in contact with the glass bottle when in operation. The plastic screw cap was tightened followed by fastening the stirring stick to the motor. A short piece of Tygon tubing was mounted on one of the metal tubes of the lid and placed a tube stopper on it. All the digesters were placed in the thermostatic water bath and connected to the CO_2-fixing bottles and to the flow cells. The agitators were connected to each agitator. The ethernet cable was connected to the internal network and to the gas volume measuring device. The power supply was connected to the outlet and to the gas volume measuring device. All the reactors were flushed with N_2 for approximately one minute, using the extra inlet on the lid to achieve anaerobic conditions. The AMPTS II software was started by logging the program.

The ratios that were used for CM: OFMSW to perform methane analysis are 1:0, 0:1, 1:1, 2:1, 3:1, 4:1, 1:2, 1:3 and 1:4 respectively. This BMP assay was performed per day, per hour and per quarter hour. Figure 3 shows conventional biogas production set-up.

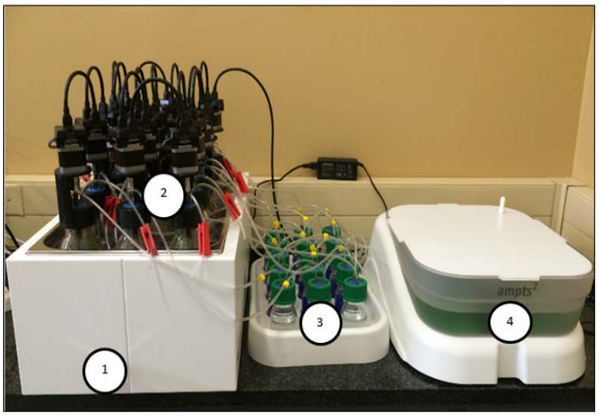

Figure 3: Biogas production set-up

Where: 1 – Thermostatic water bath, 2 - T-Glass bottle reactor, 3 – CO_2 fixing unit and 4 – Gas volume measuring device.

III. RESULTS AND DISCUSSION

The purpose of this experiment was to determine the efficiency of biogas production in mono-digestion and co-digestion processes. Chicken manure (CM) and the organic fraction of municipal solid waste (OFMSW) were mono-digested. CM:OFMSW were also co-digested at a loading rate ratio of 1:0, 0:1, 1:1, 2:1, 3:1, 4:1, 1:2, 1:3 and 1:4 respectively.

The experiment was run at mesophilic temperature 37 ^{0}C and pH of 7 under 500 ml digester. The amount of biogas produced was measured using water displacement method. As for methane content of the biogas was analyzed using a gas chromatograph (GC) with the flame-ionization detector.

Table 3: Substrate Characterization

Substrate (%)	TS	MC	VS	Ash
OFMSW	29.20	70.80	7.10	7.10
CM	76.10	23.88	9.50	9.50

Where:
MC- Moisture Content
TS – Total Solids
VS – Volatile Solids

Table 4: Elemental analysis of CM and OFMSW

Properties	Carbon (C)	Hydrogen (H)	Oxygen (O)	Nitrogen (N)
OFMSW (element %)	24,61	0,82	31,50	1,21
CM (element %)	31,81	0,85	11,94	3,11
Atomic weight (g/mol)	12,01	1,01	16,00	14,01
OFMSW (mol)	2,05	0,81	1,97	0,09
CM (mol)	2,65	0,84	0,75	0,22
OFMSW (mole ratio)	23,73	9,34	22,80	1,00
CM (mole ratio)	11,95	3,77	3,37	1,00

Table 3 and 4 shows the substrate characterisation. The total solids (TS), moisture content (MC), volatile solids (VS) and ash percentage and proximate analysis while

CNHS are ultimate analysis. TS is the sum of dissolved solids and suspended solids. TS and pH are important to assess anaerobic digestion process efficiency [20, 25]. VS is the organic portion of TS that biodegrade in the anaerobic process. TS, VS and MC are calculated using equation (2), (3), (4) respectively while C/N ratio is calculated using equation (5).

$$VS(\%) = \frac{M_{dried} - M_{burned}}{M_{wet}} * 100 \tag{2}$$

$$TS(\%) = \frac{M_{dried}}{M_{wet}} * 100 \tag{3}$$

$$MC(\%) = \frac{M_{wet} - M_{dried}}{M_{dried}} * 100 \tag{4}$$

Where:

M_{dried} = Amount dried sample (mg)

M_{wet} = Amount of wet sample (mg)

M_{burned} = Amount of burned sample (mg)

$$\frac{C}{N} = \frac{(F * C_F) + (S * C_S)}{(F * N_f) + (S * N_S)} \tag{5}$$

Where:

F = First substrate

S = Second substrate

C_f = Carbon composition for the first substrate

C_s = Carbon composition for the second substrate

N_f = Nitrogen composition for the first substrate

N_s = Nitrogen composition for the second substrate

It is observed that OFMSW has the highest percentage of moisture content. A high moisture content percentage favours optimum biogas production since it allows bacteria to release methane and metabolic processes to occur. It is due to the moisture content for waste to be broken down by anaerobic bacteria. Hence moisture is significant for optimal digestion as it aids the digestion process to yield high-quality biogas rich in methane (CH_4). The literature recommends that the moisture content for optimum conditions to be 90% [1]. Volatile solids represent the organic matter of the feedstock without considering the inorganic salts and ash. Total solids (TS) percentage represents organic and inorganic material in the feedstock.

Table 5: C/N ratio at different ratios of CM to OFMSW

Loading rate ratio for CM: OFMSW	C/N Ratio
0:1	17
1:0	10
1:1	12
1:2	11
1:3	11
1:4	11
2:1	14
3:1	14
4:1	15

Table 5 shows the C/N ratios under different loading rate. CM has a low C: N ratio; therefore it is suitable to be co-digested with the biodegradable material of high C/N ratio such as OFMSW [8]. In this experiment, the C/N ratio calculated was observed to BE 17:1 as shown in Table 5. It determines the occurrence of digestion. When the levels of C/N ratio is high, there is fast depletion of nitrogen used by the methanogenic bacteria that produce methane, to satisfy their protein needs, therefore, resulting in lower biogas production rate.

Furthermore, at low C/N ratio, the nitrogen increase causes ammonia to accumulate. This accelerates the increase in pH levels. At pH level greater than 8.5, this promotes a toxic environment for the methanogenic bacteria to exist. To operate an anaerobic digester at optimum C/N ratio biodegradable material of high C/N ratio should be blended with the biodegradable material of low C/N ratio. According to Mojapelo, N., et al. [40, 48] the optimum conditions of C/N ratio should be within 15 to 30:1

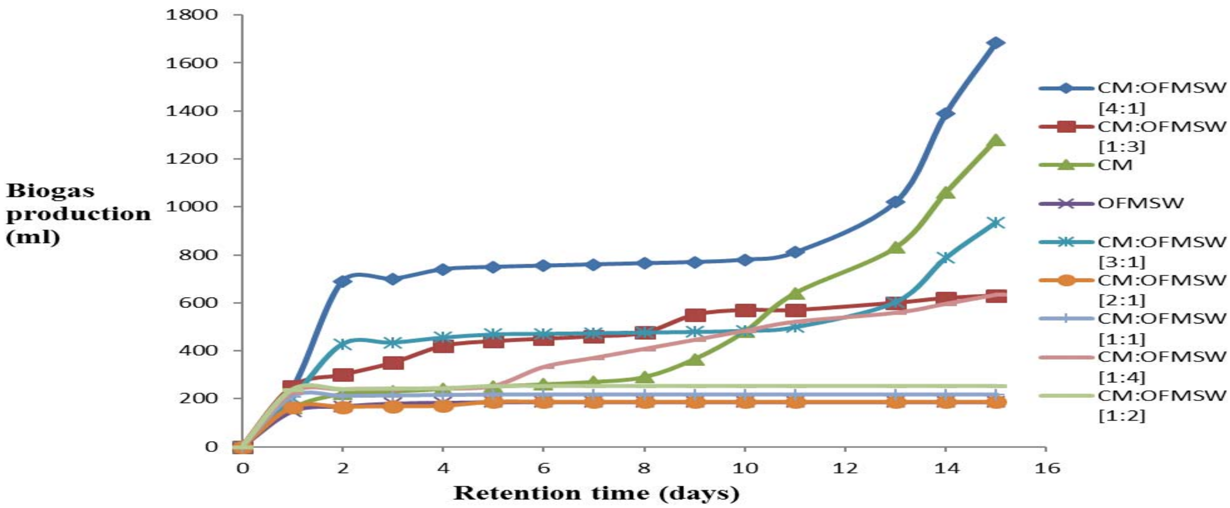

Figure 4: Biogas production for different loading rate of substrates

Figure 4 illustrates biogas production in a laboratory scale adopting water displacement method to determine the volume of biogas produced on a daily basis. It shows AD for both mono-digestion and co-digestion for CM and OFMSW in ratios. It was observed from Figure 4 that biogas production increases with retention time till the optimum point where it eases with production due to depletion of the nutrients. Hence, it can be stated that there is a directly proportional relationship between retention time and biogas production. The ratio of CM to OFMSW of 4:1 has higher daily biogas yield when compare to a ratio of 1:3 and 1:0. This was due to the high concentration of chicken manure that was rich in biogas. However, when CM was co-digested with OFMSW, it resulted to even higher amount of biogas. OFMSW are rich in protein essential for bacteria to grow and produce high-quality of biogas. This was anticipated with nutrients increase, microbial balance and VFA control in OFMSW rich in protein essential for bacteria to grow and produce high-quality biogas.

The ratio of CM to OFMSW of 1:3 had a lag phase of three days due to a low concentration of CM. The lag phase is a delay in biogas production due to uneven distribution of nutrients and temperature for bacteria metabolism. CM does not have lag phase due to the existence of active bacteria. The digester with a high concentration of OFMSW eases with the production due to depletion of nutrients within the range of 15 to 30 days.

The analysis was experimentally achieved on a laboratory scale using automatic methane potential test system (AMPTS II). In this system, biochemical methane potential tests were performed to determine the anaerobic biodegradability and optimum methane potential of waste as well as the biodegradation rate on a laboratory scale. The ratios that were used for CM: OFMSW to perform methane analysis are 1:0, 0:1, 1:1, 2:1, 3:1, 4:1, 1:2, 1:3 and 1:4 respectively. These ratios were chosen because of higher production of biogas when the fraction of chicken manure is higher than organic fraction municipal solid waste. This BMP assay was performed per day, per hour and per quarter hour.

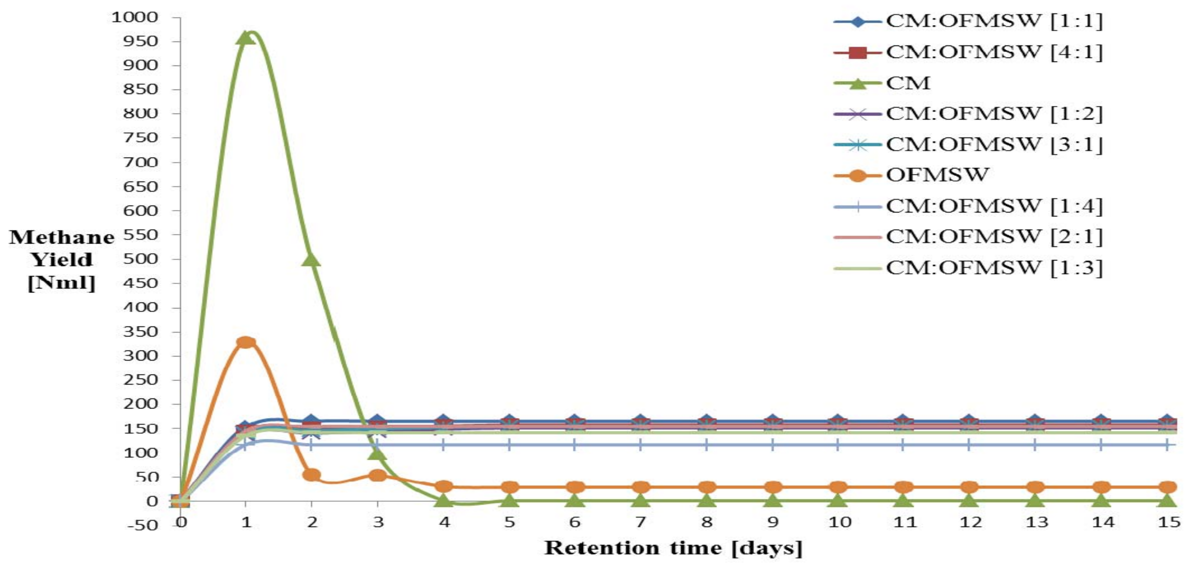

Figure 5: Methane yield per days

It was observed in figure 5 that there was a sharp increase on day one and a suddenly drop in the methane yield for mono-digestion of CM and OFMSW. This was attributed to the introduction of inoculum and even agitation to distribute nutrients and temperature. The sharp drop suggests the release of the biogas that comes with inoculum. It was also observed that the methane yield for mono-digestion of CM and OFMSW stabilizes on day five. After day five, methane yields was lowered down and stays constant with reduction of the substrate. When the substrates were co-digested, it was observed that the methane yield stays the same after day two. The yield in co-digestion was higher than in mono-digestion. Attribution is control of volatile fatty acids due to the control of pH and nutrients balance for the microbial growth. CM had higher biodegradability rate compared to ratios of CM and OFMSW. In ratio of 1:1 co-digestion using 50% of each substrate, there was optimum methane production due to balance between the amounts of bacteria present and essential nutrients available such as proteins and trace elements. The second best ratio for the production of methane was 4:1 followed by 3:1 and 2:1, as the fraction of CM in the ratios, decreases the yield of methane also decreases. However, it was the ratio of 1:1 that optimised the efficiency for the production of methane. It had the highest methane yield which was also enhanced by the mixing for 60 seconds every 60 seconds. The mixer speed was adjusted to 80 percent with the temperature kept constant at 37◦C and the possibility of overestimation was eliminated.

The operating conditions, substrate concentration and temperature were kept uniform when effective mixing was adopted. Mixing also minimized solids build up and the occurrence of scum, therefore optimising the efficiency of production of methane as expressed by Mashandate, A., et al. [26].

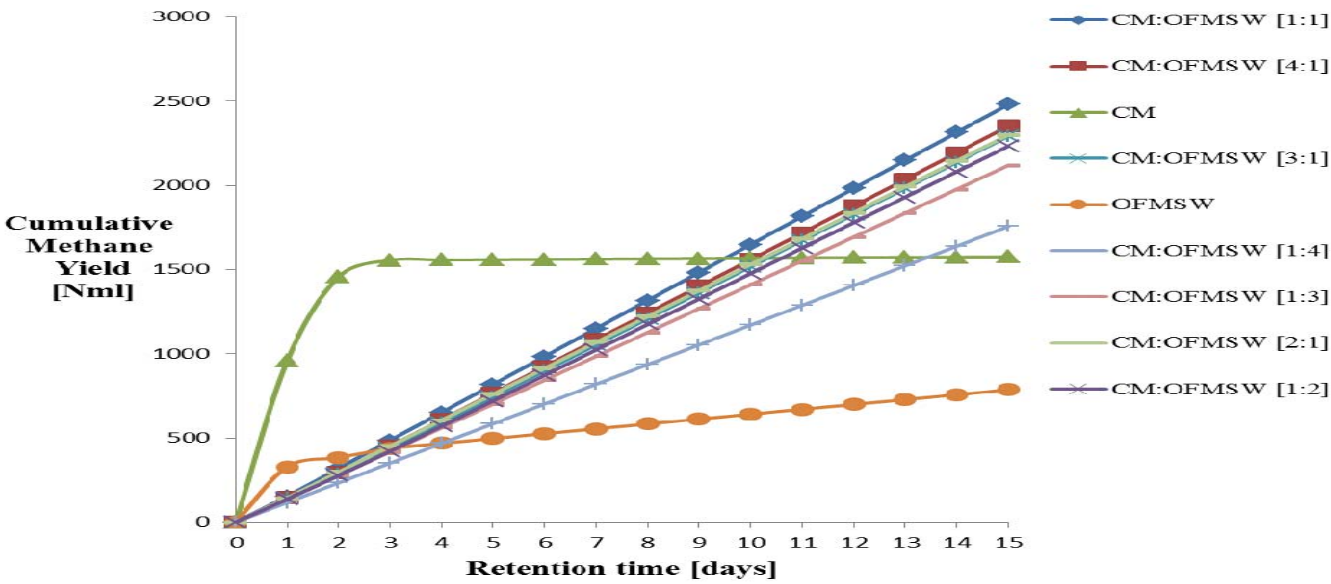

Figure 6: Cumulative methane yield per days

It was observed in figure 6 that there was a sharp increase on day one and on day two a stable methane yield was reached for mono-digestion of CM and OFMSW. When the substrates are co-digested it was observed that the methane yield has a slightly change after day two. The yield achieved after 9 days in co-digestion was higher than in mono-digestion. It could be stated that CM has higher biodegradability rate compared to ratios of CM and OFMSW. This was due to the existing bacteria in CM while in OFMSW the bacteria have to be introduced to increase the rate at which substrate was broken down. The figure 6 illustrated that the ratio of 1:1 was more efficient. In ratio of 1:1 co-digestion using 50% of each substrate, there was optimum methane production due to balance between the amounts of bacteria present and essential nutrients available such as proteins and trace elements. The second best ratio for the production of methane was 4:1 followed by 2:1, as the fraction of CM in the ratios, decreases the yield of methane also decreases. However, it was the ratio of 1:1 that optimise the efficiency for the production of methane. It had the highest methane yield which was also enhanced by the mixing for 60 seconds every 60 seconds. The mixer speed was adjusted to 80 percent with the temperature kept constant within mesophilic range 37◦C and the possibility of overestimation was eliminated.

Methane percentage was determined using Buswell formula Equation 6. This is a theoretical methane analysis.

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3 \quad (6)$$

Where:

OFMSW: a = 23, 73 b = 9, 34 c = 22, 8 d = 1

CM: a = 11, 95 b = 3, 77 c = 3, 37 d = 1

This formula makes it possible to calculate the optimum methane percentage by using feed elemental molar composition of carbon, hydrogen oxygen, nitrogen and sulphur (CHONS), however, sulphur can be assumed to be negligible. Therefore, the feed was analysed for elemental composition in the laboratory to be able to calculate for maximum achievable biogas composition. The elemental analysis was shown in table 4.2. However, in practical this biogas percentage is not achievable due to the existence of incomplete digestion. In an anaerobic digester, the bacteria feeds on the biodegradable material; and releases biogas which has a composition methane of 40% to 70% (CH_4), carbon dioxide of 30% to 60% (CO_2) and other traces elements such as ammonia (NH_3), hydrogen sulphide (H_2S) and hydrogen (H_2) [14].

Table 6: Theoretical methane and C/N ratio at different ratio of CM to OFMSW

CM: OFMSW	Methane [%]
00:01	36
01:00	44
01:01	40
01:02	42
01:03	42
01:04	43
02:01	39
03:01	38
04:01	38

Table 6 show the optimum methane for different feed ratios. In the mono-digestion of CM, it shows a higher percentage of methane which was 44% while mono-digestion of OFMSW has maximum methane of 36%. Co-digestion of this substrate with a ratio of CM to OFMSW for 1:4 results to 43% methane which was the best improvement of OFMSW methane percentage. However, for 2:1, 3:1 and 4:1 methane percentage was 39, 38 and 38 respectively. This was due to the reduction of OFMSW fed; therefore the bacteria had a shortage of nutrients.

IV CONCLUSION

It was concluded that in experimental work under laboratory scale using conventional biochemical methane potential assay, the ratio 4:1 had optimum biodegradability rate than other ratios which were investigated, while the ratio of 1:1 has optimum biogas and methane yield after a retention time of 15 days. Co-digestion of OFMSW and CM stabilizes conditions in anaerobic digestion process such as C/N ratio in the substrate mixtures as well as macro and micronutrients, pH, inhibitors or toxic compounds and dry matter. These increases biogas production compared to mono-digestion. The waste generated in the city's landfills could be co-digested with CM to produce methane which can be used as a source of useful energy for transport sector, industries and homes biofuel and electricity production.

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