Biogas production from solid food waste and its use for electricity production

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Declaration

I, Selebogo Mervyn Khune, declare that this dissertation is my original work achieved through scientific research, personal reading and consultations with my supervisors. It has not been presented for the award of a degree in any other institution.

Signature…………… Date 15 October 2021 ……………………… Place Vanderbijlpark ……………………………

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This project began with a great deal of curiosity on how cooking gas can be generated in a backyard from organic waste. I was able to find answers to this phenomenon with the help of passionate people:

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Dedication

To my wife, Mabotle Mulungwa and mother, Maria Khune

List of publications

Mervyn Khune, Benton Otieno, Peter Osifo and Aoyi Ochieng (2021). Solar heated bioreactor using food waste for enhanced biogas production and electricity generation. *Submitted to Southern African Sustainable Energy Conference.* Western Cape, South Africa, 11-13 August 2021(under review)

Mervyn Khune, Benton Otieno, Peter Osifo and Aoyi Ochieng (2021). A comparative study of the psychrophilic and mesophilic pilot-scale anaerobic digestion of food waste. *Submitted to Euro-Mediterranean Journal for Environmental Integration.*Sousse, Tunisia, 10-13 June 2021(under review)

Abstract

An enormous amount of food waste (FW) is generated worldwide. Most of this waste is discarded in landfills, where it undergoes uncontrolled anaerobic digestion (AD) process, which emits excessive amounts of greenhouse gases, (methane and carbon dioxide), thereby contributing to global warming. A controlled AD of FW is key for organic waste management with a positive impact on the environment and economy. In South Africa (SA) there is little uptake of biogas technology for FW management due to little research on biogas potential at small to large scale. Furthermore, there is an over reliance on foreign data, which leads to misfit parameters to local raw materials; consequently, producing biogas of low quality and quantity with low degradation of waste. Biogas with poor quality reduces the efficiency of biogas conversion to energy and the low production rate makes the system less feasible. Considering the challenges faced with FW management and the little uptake of the AD technology in SA, this study aimed to treat FW through AD and convert the biogas produced to electricity. A complete-mix biogas pilot plant (VUT-1000C) was designed, constructed and commissioned. The materials used for constructing the pilot plant were sourced locally to prove the applicability of the AD technology in SA. The biodigester was operated at mesophilic temperature, 37 ^{o}C, aided by a solar system. A stand-alone 1 m^3 plug-flow ambient biodigester (STH-1000A) was operated semi-continuously as well as a control. Cow dung (CD) was used to inoculate the biodigesters, which were then operated semi-continuously at their optimum organic loading rate (OLR). The STH-1000A digester was operated at 0.446 kgVS/m^3/day OLR, according to the manufacturer's specification, while for VUT-1000C, the OLR was determined. The highest biogas and methane yields obtained were 582 and 332 L/kgVS/m^3, respectively, at the determined optimal OLR of 1.5 kgVS/m^3/day for the VUT-1000C digester this was supported by the modified Gompertz model with an R^2 value of 0.9836. VUT-1000C produced 1200 L/day while STH-1000A produced 150 L/day. VUT-1000C proved to be a more effective biodigester than STH-1000A owing to the digester design and operation at mesophilic conditions. The key design findings are higher reactor working volume and high digester temperature. From the 1000 L of biogas produced from VUT-1000C, 1.8 kW of electricity was generated, which is equivalent to powering 300 6W light bulbs for 1 hour. The energy balance of the pilot plant showed that only 10 percent of the energy output was required to operate the plant. These results show that SA has a 475 GWh energy potential based on the current FW figures. Furthermore, the study has shown

that biogas technology is readily available for South Africans and that the designed biogas plant was very efficient in FW-to-energy conversion.

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Abbreviations and Acronyms

AD	Anaerobic digestion
CD	Cow dung
CHP	Combined heat and power
COD	Chemical oxygen demand
F/M	Food to microorganism
FW	Food waste
GDP	Gross domestic product
GFS	Glass-fused-to-steel
GHG	Green house gas
HDPE	High density polyethylene
LLDPE	Linear low-density polyethylene
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
PVC	Polyvinyl chloride
TS	Total solids
VFA	Volatile fatty acids,
VGPR	Volumetric gas production rate
VS	Volatile solids

Symbols

B_p	Biogas production potential (L)
B_t	Cumulative biogas produced (L) at a given time
BY	Biogas yield (L/kgVS)
COD	Chemical oxygen demand (mg/L)
E_{biogas}	Biogas volume (L)
FW	Food waste (kg)
k_1	First order reaction rate constant (hr^{-1})
OLR	Organic loading rate (kgVS/m^3/day)
R_b	Maximum biogas production rate (L/hr)
TVS	Total volatile solids (kgVS)
TS	Total solids (kg)
VGPR	Volumetric gas production rate (m^3/day)
VS	Volatile solids (kg)

Greek symbols

λ Lag phase (hrs)

CHAPTER 1: INTRODUCTION

1.1 Background of the study

Throughout the world food supply chain, 1.3 billion tonnes of food is wasted yearly (Gustavsson, Cederberg, Sonesson, van Otterdijk&Meybeck2011). This is causing environmental, economic and social problems (Xu, Li, Ge, Yang & Li 2018). Many sectors in South Africa are being strained due to the growing population, particularly for energy supply and waste management. South Africa produces 28 million tons of food and a third of it is discarded as waste (Oelofse & Nahman 2013). According to Nahman and de Lange (2013), the total cost of food waste (FW) across South Africa's food value chain is estimated to be R61.5 billion per annum (approximately US$7.7 billion), which is equivalent to 2.1% of South Africa's annual gross domestic product (GDP). Current methods of organic waste disposal are incineration, landfills, composting and anaerobic digestion. Incineration and composting require energy to operate, while landfilling has been considered the most practical and cheapest disposal method. However, landfills are filling up quickly and this creates the need for more sites farther away from waste generation, thereby increasing costs.

More than 50% of the waste disposed in landfills and on street corners is organic and rots under uncontrolled anaerobic conditions, releasing landfill gas into the atmosphere and leachate into underground water (FullCycle 2009; DEA 2012; de Lange & Nahman 2015). Landfill gas, also known as biogas, comprises primarily of 55 – 70% methane, 30 – 45% carbon dioxide and trace amounts of hydrogen sulphide (0-2000 ppm), moisture (depending on temperature) and siloxanes (Priebe, Kipper, Gusmao, Marcilio & Gutterres 2016). Methane is 25 times more potent than carbon dioxide as a greenhouse gas. Hydrogen sulphide produces bad and unhealthy smells in the area. The disposal of organic waste to landfills contributes 4.3% to South Africa's greenhouse gas emissions. Throughout the food supply chain to landfill, greenhouse gas emissions range between 2.8 and 4.14 t CO_2 per tonne of FW (Oelofse & Nahman 2013). The national waste sector landfills contributed 18 773 Gg CO_2 eq to the national methane emissions in 2010 (DEA 2014).

The controlled anaerobic digestion of FW (and other organic waste) is considered a key element in organic waste management due to its positive impact on the environment, economy and energy (Kang & Yuan 2017). It is a net energy producing process, 100-150 kWh/ton of waste (Braber, 1995). This treatment method reduces the emissions of greenhouse gases going into the atmosphere while producing carbon-neutral renewable energy and biofertiliser. Anaerobic digestion is a biological degradation treatment of organic substrate undertaken by microorganisms in an aqueous environment in the absence of oxygen (Appels, Lauwers, Degreve, Helsen, Lievens, Willems, van Impe, &Dewil2011; Sawatdeenarunat, Surendra, Takara, Oechsner & Khanal 2015). The substrate must be sufficiently bloated with at least 50% water (Vindis, Mursec, Rozman, Janzekovic & Cus 2008). The balanced methane fermentation process is carried out by symbiotic fermentative bacteria: syntrophic acetogens, homoacetogens, hydrogenotrophic methanogens and acetoclastic methanogens (Chen, Guo, Ngo, Lee, Tung, Jin, Wang& Wu 2016). Methane, being the main constituent, is a fuel constituting up to 99% of natural gas. The concentration of impurities varies with different treated wastes. Methane has a calorific value of 36 MJ/m^3 and thus biogas has a calorific value of 22 MJ/m3 at 60% methane composition (Nielsen 2002). The calorific value of biogas can be improved by biogas purification. Biogas can be used for cooking, generating electricity in combined heat and power plants (CHP) and as a vehicular fuel. One m^3 of biogas can produce 2.1 kW of electricity assuming a mechanical efficiency of 35% for the generator.

The generation of electricity from biogas is seen as one of the most dominant future renewable energy sources, because the continuous power generation from organic waste can be guaranteed (Appels *et al.* 2011). South Africa’s primary energy source is coal and is responsible for carbon dioxide emissions contributing to 12% of greenhouse gas emissions globally. According to Statistics South Africa (Lehohla 2013), almost 90% of 236 TWh of electricity is generated in coal-fired power stations, 5% from nuclear, 0.5% hydroelectricity, 2.3% natural gas, 0.01% wind and 1.3% from pumped storage schemes (Lehohla 2013). The national landfill methane emission is equivalent to 101 TWh of electricity, half of South Africa’s energy generation. 3 GWh can be generated from the estimated national 9 Mt of FW (the amount of FW could be understated due to the lack of sufficient records) turning on 522 million 6W light bulbs. Power generated from biogas is carbon-neutral and thus environmentally friendly.

Past research has shown FW to have high degradability properties and highly suitable for anaerobic digestion to produce biogas energy (Zhang, El-Mashad, Hartman, Wang, Liu, Choate & Gamble 2007). Optimal conditions can be determined for the use of the technology in South Africa - even at household and restaurant level (at pilot scale) and then taught at schools and universities. Biogas and biofertiliser are not used enough in South Africa and need to be showcased as a working solution in South Africa at all stages, small to large scale (Tiepelt 2015). The deficiency of human skills to design, implement and operate biogas plants safely and effectively is one of the reasons that there has been little employment of the technology in South Africa (Greben &Oelofse 2009). Thus, the importance of constructing a pilot plant using locally sourced material and thenoptimising the digester, yielding real world results. The digester will be built in the most efficient way with locally available material to provide a long-lasting technology and produce enhanced biogas for electricity generation.

1.2 Motivation for the study

Organic waste materials from restaurants, municipalities, wastewater treatment plants and industries can be converted into clean energy by anaerobic digestion. From anaerobic digestion, two products are extracted: biogas and biofertiliser. This method addresses the issue of waste disposal and reliance on fossil fuels. In India, there are 12 million biogas plants, 17 million in China, about 8000 in Germany, 600 in Uganda and only 300 in South Africa (Mukumba, Makaka& Mamphweli2016; Munganga 2013). These countries have a widespread application of biogas and research work. This project aims to add to biogas application research in South Africa at a pilot scale and will also add to South Africa's database on the potential of electricity generation from biogas from kitchen FW.

1.3 Significance of the study

Given the challenges faced in FW management, especially in reducing the costs associated with the disposal of FW and the little uptake of AD technology, this research has identified an efficient treatment method that has a positive net energy and designedandconstructed an efficient reactor to treat FW. The study had identified durable and cost-effective materials of construction for a pilot-scale digester that can last more than 10 years and produce enhanced biogas. This setup can be used at household and restaurant level and the materials of construction are readily available at local hardware shops.

1.4 Problem statement

Approximately 9 million tons of FW is generated in South Africa along the food supply chain annually (Oelofse &Nahman 2013). In South Africa, households and restaurants produce large amounts of waste, some of which is disposed of in illegal dumping sites. More than 50% of the waste disposed of in landfills and on street corners leads to uncontrolled emissions of methane, which is a greenhouse gas under anaerobic conditions (FullCycle 2009). To mitigate the potential environmental, social and economic effects associated with the poor disposal of FWs, several treatment technologies have been proposed, whereby the otherwise FW is considered as a potential resource (Greben &Oelofse 2009). Of the conventional treatment methods for this type of waste, anaerobic digestion is a widely preferred option aiming at biogas production.

In South Africa, there is little uptake of anaerobic technology for FW management due to little research on biogas potential at small- to large-scale studies (Mukumba *et al*. 2016). Furthermore, the challenge with current biogas utilisation is the reliance on foreign data; this leads to a mismatch of parameters to local raw materials and conditions. As a result, biogas of low quality and quantity is produced and low biodegradation of wastes is obtained. Poor quality biogas reduces the efficiency of biogas conversion to energy and low production rate of quantity makes the system less feasible. It is thus necessary to carry out local studies on the anaerobic digestion of FW. To ensure applicability, pilot-scale studies, using locally assembled anaerobic reactors are very necessary. Process optimisation is very important for the maximum generation of biogas with high methane yield. It is also important to carry out energy analysis of the anaerobic treatment and determine the potential conversion of the biogas produced to heat and electricity.

1.5 Aim

To carry out anaerobic digestion of food waste and determine the potential of generating electricity from the biogas produced.

1.6 Specific objectives

The specifics objectives are:

i. To design, construct and commission a pilot scale anaerobic digester for food waste degradation;

ii. To determine optimal operating conditions for the anaerobic digester for maximum biogas production and methane yield;

iii. To convert the biogas generated at optimum conditions into electricity; and

iv. To carry out energy analysis of the anaerobic digester unit.

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CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The climate of a place is the average weather over years. Though the weather can change in just a few minutes, climate changes over hundreds, thousands, even millions of years. The weather and climate are important to life on earth for the creation of a habitable environment. Over the past 50 years, the global temperature has increased at the fastest rate recorded in history(KARL, ARGUEZ, HUANG, LAWRIMORE, MCMAHON, MENNE, PETERSON, VOSE& ZHANG 2015; NOAA 2015). The increase in global temperature, known as global warming, is caused by air pollution that leads to the accumulation of heat-trapping greenhouse-gases in the atmosphere. These gases absorb and trap solar radiation that has bounced off the earth's surface and destined to escape into space. Greenhousegases can last for years to centuries in the atmosphere.Sources of air and water pollution include fuel combustion in vehicles, heat and power generation, industrial facilities, municipal and agricultural waste sites (landfills), waste incineration/burningand residential cooking, heating and lighting with polluting fuels.

In South Africa, human activity increased with the increase in the population and urbanisation. This led toan increased power demand and larger waste streams. The main source of power is from coal-fired plants, which emit high amounts of greenhousegases, including carbon dioxide and methane, into the atmosphere. The disposal of organic waste, especially food waste (FW), also has dire consequences to the environment. Landfills emit greenhousegases, which contain mainly methane and carbon dioxide with other gases in small quantities. Leachate, from the landfill of organic matter, pollutes water by seeping into underground water bodies. The current chapter provides an overview of the generation and characteristics of FW, evaluates the use of anaerobic digestion for FWremediation and further presents the potential of biogas as a renewable source of electricity.

2.2 Global food waste production

FW could be defined as food initially produced or purchased for human consumption but which has remained unused by humans (GRIFFIN, SOBAL& LYSON2009). The waste is composed of cooked, uncooked, edible and inedible food materials that may be generated before, during and after meal preparation in households and restaurants. Food wastage also occurs in the process of food manufacturing, distribution, retail and food service activities (European Commission 2010).

Globally FW is increasingly becoming anissue. A study conducted in the United Kingdom showed that a third of food purchased by consumers is thrown away, with two thirds of the lost food being edible (Waste Resources and Action Programme 2008). The most common reason for wasting food was that too much was cooked,prepared, or purchased. Even in pre-consumption stages food, waste occurs and due to the lack of or failure of infrastructure, food loss or spoilage occurs (Lundqvist, De Fraiture,& Molden 2008; Parfitt, Barthel & Macnaughton2010). On a global scale, it is estimated that throughout the food supply chain food, waste as much as 50% of all grown food is lost or wasted before and after it reaches the consumer (Lundqvist *et al*. 2008). A study conducted by Gustavsson *et al.*(2011) estimate that a third of food produced for human consumption is lost or wasted globally, amounting to approximately 1.3 billion tons per year.

According to Fao (2011),developed countries produce more food loss and waste than developing countries. Developed countries such as North America, Oceania, Europe and the industrialised Asian nations of China, Japan and South Korea contributed 56% to the total global food loss and waste whereas the developing countries accounted for 44% of the loss (Figure 2.1).

The distribution of this FW along the food supply chain varies significantly between developed and developing countries. In preliminary research, it has been found that most FW in developing countries occurs mostly on farms during harvesting, transporting and storage, whereas in developed countries, food is mostly lost in the consumption stage; in households and restaurants (Allafrica 2010 and Ramukhwatho 2014).Figure 2.2indicates that in North America, Oceania and Europe,more than half of the food loss and waste occurredat consumption. Whereas in South and Southeast Asia, and in Sub-Saharan Africa two-thirds and three-quarters, respectively, of food losses and waste occurred during the production and storage stages. This distribution outlined in Figure 2.2suggests that efforts to recover food loss and waste should focus on pre-consumption stages in most developing countries and focus on post-production stages in developed countries.

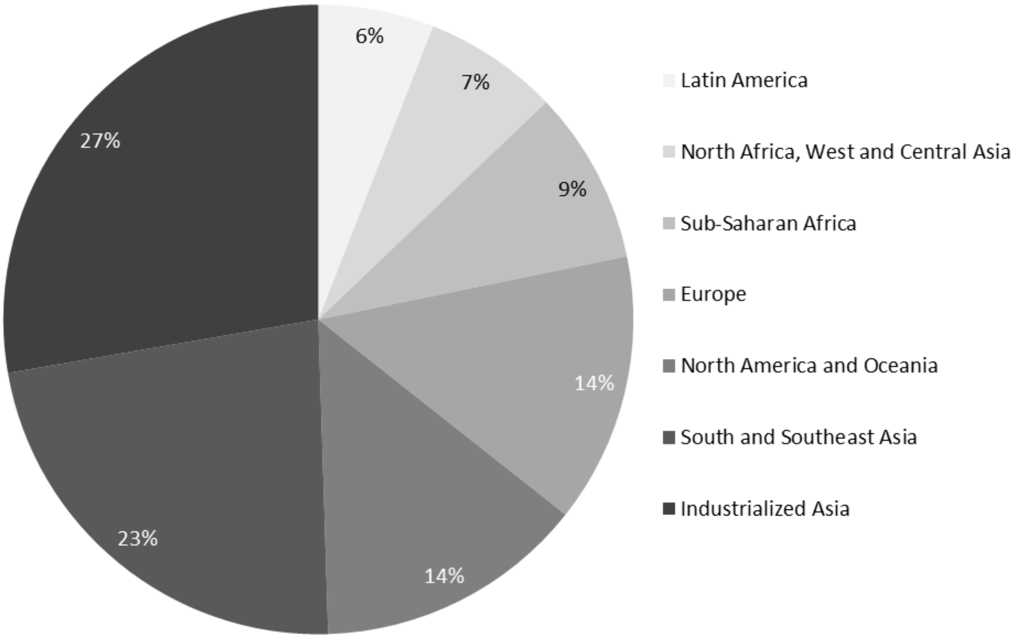

Figure 2.1: Share of global food loss and waste by region (Fao 2011)

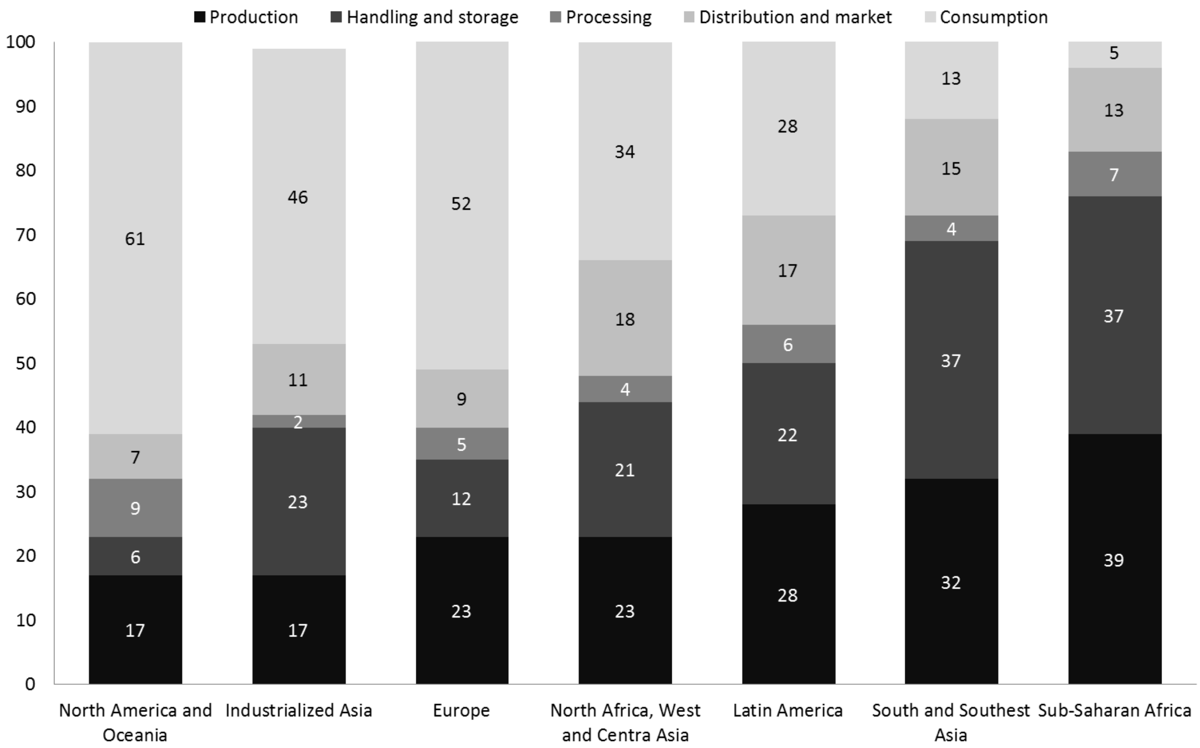

Figure 2.2: Food lost or wasted by region and stage in value chain (Fao 2011)

However, research by Ogola, Chimuka & Tshivhase (2011) and Lipinski, Hanson, Lomax, Kitinoja, Waite & Searchinger(2013) shows that almost all urban areas with high income reported high portions of FW, regardless of whether they are located in developed or developing countries. Lipinski *et al*. (2013) added that cities located in developing countriesmay have higher levels of waste and fail to address this problem due to the lack of infrastructure. Enormous amounts of this food lost or wasted ends up in landfills globally. According to a report by Fao (2013), a smallamount of all food wastedis composted or recovered, most of it ends up in landfills and it comprises a large part of the municipal solid waste. The emission of methane from landfill is one of the largest sources of GHG emissions from the waste sector. About 3.3 billion tCO_2 equivalent of GHG per year, from food wastage carbon footprint, is released into the atmosphere (Fao 2013).

2.3 Food waste production in South Africa

South Africa produces an average of 28 785 000 tons of food per year as per 2007 to 2009 Faostat (2010) records.The production amounts per commodity group in South Africa are listed in **Erreur ! Source du renvoi introuvable.**. Cereals, fruits and vegetables account for most of the produced commodities averaging at 13 154 000 and 8 229 000 tons, respectively, which is a combined 74% of total production.The remaining 26% is made up of the rest of the commodities, with the least produced being fish and seafood and oil seeds and pulses.

Table 2.1: Food production per commodity group in South Africa (Oelofse &Nahman 2013)

Commodity Group	**Production (1000 tons)**			
	2007	**2008**	**2009**	**Average**
Cereals	9514	15363	14586	13154
Roots and Tubers	2023	2147	1882	2017
Oil seeds and Pulses	261	535	563	453
Fruits and Vegetables	8109	8417	8162	8229
Meat	2138	2179	444	1587
Fish and seafood	673	No data	No data	224
Milk	3066	3200	3091	3119
Total Production	**25785**	**31841**	**28729**	**28785**

It is estimatedthat a third of the total food produced in South Africa is wasted (Oelofse & Nahman 2013).Wastages occur at different stages of the food supply chain. The food supply chain has five categories, namely agriculture, post-harvest handling and storage, processing and packaging, distribution and consumption. A staggering 96%ofFW is generated during the pre-consumption stages as outlined in Table 2.2, equivalent to 8.67 million tonnes. Losses during agricultural production, post-harvest handling and storage and processing and packaging share similar splits of 26%with distribution accounting for 17% of the 96%. At the consumption stage, only 4.1% of the agricultural production is lost, equivalent to 0.37 million tonnes.Fruits and vegetables contribute a large portion of the total waste per commodity group (47%)while the rest of the commodities make up the other half.

Table 2.2: South Africa's food waste by weight and percentage for each step of the food supply chain for selected commodities (Oelofse &Nahman 2013)

Commodity	**Waste 1000 tons (%)**					
	Agriculture	**Post-harvest handling and storage**	**Processing and packaging**	**Distribution**	**Consumption**	**Total waste per commodity group**
Cereals	789.9 (8.7)	989 (10.9)	398 (4.4)	220 (2.4)	108 (1.2)	**2504.9 (27.7)**
Roots and Tubers	282.4 (3.1)	312(3.5)	213(2.4)	60 (0.7)	23(0.3)	**890.4(9.8)**
Oil seeds and Pulses	54.4(0.6)	32(0.4)	29 (0.3)	7(0.1)	3 (0.0)	**125.4(1.4)**
Fruits and Vegetables	823(9.1)	667(7.4)	1685 (18.6)	859 (9.5)	210 (2.3)	**4244 (46.9)**
Meat	238.1 (2.6)	9 (0.1)	67(0.7)	89 (1.0)	24 (0.3)	**427.1 (4.7)**
Fish and seafood	12.8 (0.1)	13 (0.1)	18(0.2)	27(0.3)	3 (0.0)	**73.8 (0.8)**
Milk	187.1 (2.1)	323(3.6)	3 (0.0)	261 (2.9)	2(0.0)	**776.1 (8.6)**
Total per stage of food supply chain	**2387.7 (26.4)**	**2345 (25.9)**	**2413 (26.7)**	**1523 (16.8)**	**373 (4.1)**	**9041.7 (100.0)**

2.4 Food production in institutions of higher learning waste

Higher learning institutions in South Africa produce significant amounts of FW, which can be easily turn into energy and compost. Most universities and restaurants dispose their FW to landfills or donate to pig farmers in the area. According to Roos (2016), the North-West University produced 70 kg and 250 kg of FW per week from De Jonge Akker and

Drakenstein restaurants, respectively. The FW was either disposed of at landfill sites or donated to pig farmers in the area.None of the FW is composted or recovered. The same applied for the Vaal University of Technology and Stonehaven producing 350 kg and 500 kg of FW per week. Rhodes University produces 450 tons of FW per year (Painter, Thondhlana& Kua2016) and Stellenbosch University at their main campus produced 3500 kg of FW per week was collected from 22 residences for 42 weeks per annum. At Stellenbosch University, the storage of large amounts of FW until disposal occurred, posed a safety challenge. Marais, Smit, Koen& Lötze (2017) reported that this problem was compounded by the fact that organic waste is no longer accepted in landfills by many municipalities.

2.5 Characteristics of food waste

The biodegradability of a substance depends on its physical-chemical characteristics. These characteristics influence the performance of anaerobic digestion by affecting the methane yield and process stability (Zhang *et al*. 2007). Some of the typical characteristics of domestic FW are given in Table 2.3.FW contains both high moisture and organic content.Yirong, Zhang, Heaven & Banks(2017) obtained 90.5%,Zhang *et al.* (2007) 69.1%,Zhang, Leeb & Jahnga (2011) 81.9%, Zhang, Xiao, Peng, Su & Tan (2013) 76.9% and Kuczman, Gueri, Souza, Schirmer, Alves, Secco, Buratto, Ribeiro& Hernandes(2018) 84.7%.The pH of FW is typically acidic, Zhang *et al.* (2011) found a value of 6.5, Zhang *et al.* (2013) 4.2 and Kuczman *et al.* (2018) 5.98. The decrease in pH value is greatly affected by the length of FW storage before digestion (Daly, Usack, Harroff, Booth, Keleman & Angenent2020).

Table 2.3: Typical domestic food waste characteristics

Parameters	**Yirong *et al.* (2017)**	**Zhang *et al.* (2007)**	**Zhang *et al.* (2011)**	**Zhang *et al.* (2013)**	**Kuczman *et al.* (2018)**
pH	-	-	6.5	4.2	5.98
TS (%)	23.9	30.9	18.1	23.1	15.3
VS (%)	21.6	26.4	17.1	21	13.0
VS (% TS)	90.5	85.3	94	100	85.2

2.6 Environmental effects of food waste

Organic waste such asFWis problematic, as waste streamsto landfills, where it contributes to greenhouse gas emissions (Hartman & Ahring 2006). There are numerous problems associated with organic waste mismanagement;however, in this study, the problem of greenhouse gas (GHG) emissions is discussed. Along the food supply chain, the GHG emissions average between 2.8 and 4.14 tons of carbon dioxide (tCO_2e) per ton of food (Oelofse& Nahman 2013). Agricultural production, manufacturing and processing stages contributed between 1.95 and 2.29 tCO_2e per ton of food, distribution and retail: between 0.1 and 0.8 tCO_2e per ton of food, consumption: between 0.3 and 0.6 tCO_2e per ton of food and end-of-life (landfill): 0.45 tCO_2e per ton of food. From these figures it can be concluded that inefficiencies in the food supply chain have the potential to contribute 4.14 tCO_2e per ton of food wasted, contributing a significant amount to South Africa's greenhouse gas emission footprint (Oelofse & Nahman 2013). According to DEA (2009),agriculture and disposal of organic waste (including FW) contribute 9.3 and 4.3% respectively, to South Africa's GHG emissions. Appropriate recovery methods for the generated FWare thus necessary.

2.7 Organic waste disposal methods

In South Africa, landfilling is considered to be low-cost and the most practical waste management method (Oelofse & Nahman 2013). However, factors such as the lack of land in close proximity to areas of waste generation make landfilling expensive and many active landfill sites in South Africa are currently under pressure to close (Jewaskiewitz 2008). Organic waste in landfills undergo anaerobic digestion and consequently release GHG emissions.These landfill gases with high concentrations of methane and carbon dioxide and increased costs have made landfilling a less attractive waste management option (Hartmann & Ahring 2006).Landfilling is outlawed in many countries, including Germany, Sweden, Canada; and the phasing out of these practices is now also a priority in South Africa (Oelofse & Nahman 2013).Methane is a GHG that is 25 times more potent than carbon dioxide in trapping heating in the atmosphere (Ramukhwatho et al. 2014). Furthermore, the decomposition of FW results in leachate that can potentially seep into water bodies and pollute it (Aderemi, Oriaku, Adewumi & Otitoloju2011).The environmental impact of the landfilling contributes to climate change and global warming and water pollution. This means municipalities need to adopt technologies and processes that will convert organic waste to biogas and fertiliser. Using the generated waste as a resource is important in the context of a circular economy and sustainable processes.Of the several technologies, anaerobic digestion (AD) has been considered for energy recovery and may be used for converting the organic FW into biogas and fertiliser for agricultural applications (Greben&Oelofse 2009).

2.8 Anaerobic digestion of food waste

Anaerobic digestion is commonly used in wastewater treatment plants and has been successful in sludge treatment processes for many years (Apollo, Onyango & Aoyi2013).The earliest documented successful application of anaerobic digestion in South Africa was in 1957 on a pig farm (Mother Earth News 1973). FW has now gained attention globally as a high-moisture, energy-rich and widely available feed for anaerobic digestion (Xu *et al.* 2018). It has been recognised as an environmentally friendly technology to convert FW into renewable energy (Ratanatamskul, Onnum& Yamamoto 2014). The technology has been applied gradually at pilot scale in households and restaurants (Kuczman *et al.* 2018). Most large-scale applications of the anaerobic digestion of FW are based on co-digestion with either wastewater or manure (Hegde & Trabold 2019). As FW amounts increase, large scale anaerobic digestion of FW only needs to be considered.

2.9 Anaerobic digestion process

The process takes place in four key steps: (i) hydrolysis, (ii) acidogenesis, (iii) acetogenesis and (iv) methanogensis, as demonstrated in Figure 2.3. It is through these stages that biomass is converted to biogas. The process is carried out by each group's product becoming feed for the subsequent group. This shows the interdependentness of the bacterial groups on one another for the production of the desired final product.

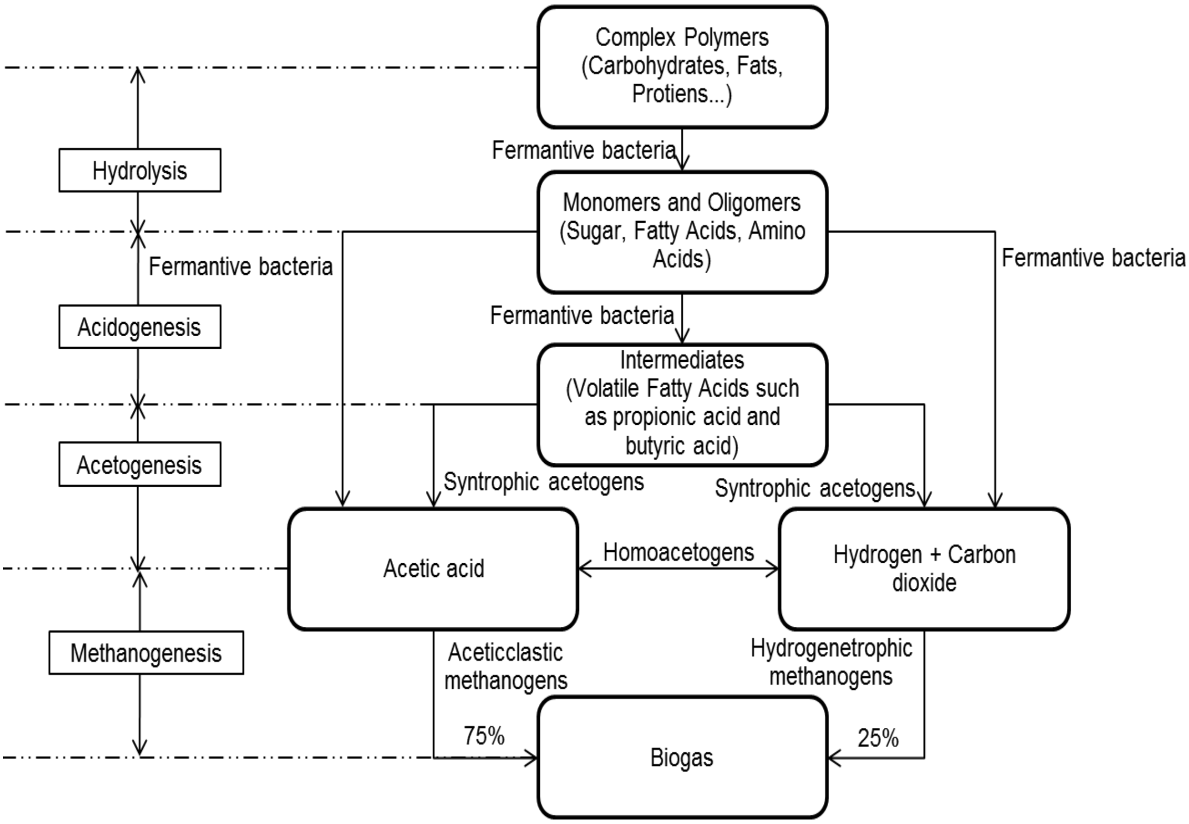

Figure 2.3: A schematic diagram showing the comprehensive processes of biogas production from anaerobic processes (Chen *et al*. 2016)

In the first stage, matter is broken down into smaller components; complex polymers break down to monomers and oligomers. These monomers and oligomers are formed into butyric and propionic acids by acidogenic bacteria that are hard and can tolerate a wide range of conditions. Contrary to this, the acetogenic bacteria have an optimal pH level nearest to 7, the pH at which a digester should be maintained. During acidogenesis and acetogenesis significant amounts of hydrogen and carbon dioxide are generated. The final stage is the ultimate stage where biogas is produced and this is carried out by methanogens, methane forming bacteria. These bacteria have a slower growth rate than the acid-forming bacteria and thus this stage is rate limiting (Fenchel, King& Blackburn2012; Chen *et al*. 2016). This is also the most sensitive stage to inhibitors such as ammonia, temperature, pH and other operating conditions. Therefore, it is crucial to retain sufficient slow-growing methanogenic bacteria, limit inhibitory levels and prevent active biomass from exiting the digester prematurely (Chen *et al*. 2016).

2.10 Factors affecting biogas production

The production of biogas is affected by many factors, which make up the environmental conditions the microbial activity takes place. According to Dobre, Nicolae& Matei(2014), temperature is a critical parameter to consider. Different groups of bacteria/microorganisms are stimulated at different temperatures, while others are inhibited simultaneously inducing various degrees of material biodegradability. Digester temperature also influences the quantity and quality of biogas. Furthermore, biogas quality and quantity are influenced by theinitial bacterial culture, biodegradable organic matter content of the feedstock, feedstock particle size, concentration of solids, digestate pH, digester agitation/mixing and the type of digester used.

2.10.1 Temperature

One of the critical operating parameters is temperature. The temperature inside the digester has a huge impact on biogas production. A digester can operate in three temperature ranges: (a) the low temperature, psychrophilic bacteria range, that is less than 20ºC; (b) the medium temperature, mesophilic bacteria range, that is 20 to 40ºC; and (c) the high temperature, thermophilic bacteria range, that is 50 to 55ºC. Higher temperature ranges produce higher yields of biogas,however, an additional source of energy might be required to maintain the digester at constant higher temperature (Imam,Khan, Sarkar & Ali2013). According to Yadvika, Sreekrishnam, Kohli& Rana(2004), anaerobic digestion is most active in mesophilic and thermophilic temperature ranges and the retention time is affected by temperature. When NH_3 concentration is high, the process is most stable and gives higher biogas yields below 55^{o}C; this is indicated by VFA concentration reduction (Yadvika *et al.* 2004).

Stability of digester temperature is crucial; Garba (1996) and Yadvika *et al*. (2004) observed that methanogens are very sensitive to drastic temperature changes. Therefore, when building a digester, it important to insulate the digester from cold winds and have it facing the sun. Insulation helps keep the digester in desired temperature range (Molnar & Bartha 1989; Yadvika *et al*. 2004). A biogas plant using solar energy for heating in a polyvinyl chloride (PVC) greenhouse type structure was able to raise the digester temperature from 18^{o}C to 37^{o}C. During winter solar assisted digesters obtained high biogas production (Tiwari

&Chandra 1986; Yadvika *et al*. 2004). The use of hot water during slurry preparation can also improve biogas production.

2.10.2 pH

The methanogenic bacteria require a pH between 6.8-8.2 and this was also proven to be an optimum level for digestion, according to Gunnerson and Stuckey (1986) and Thom (1994). The presence of various acids and bases in the slurry contributes to the overall pH in the digester. VFAs such as acetate produced during acidogenesis lower the pH. The digestion reaction system provides its own buffering capacity to resist pH changes to 6.3 that involves bicarbonate ion and carbon dioxide. The alkalinity and buffering capacity available in the digester can be measured in milligrams of calcium carbonate per litre of slurry. Acid buildup in the digester is indicated by a drop in pH below 6.8, which is attributed to a number of factors, typically sudden changes in operating conditions: loading rate, digester temperature, introduction of toxins and inconsistent substrate material. In an instance where there has been a sudden increase in loading rate, the acidogenesis and acetogenesis will tend to increase, producing more acids. However, the methanogensis has a low growth rate and will not be able to use all the acids produced, resulting in an accumulation of acids (Thom 1994).

2.10.3 Seeding

Anaerobic digestion can be a very slow process and the production rate can be accelerated by introducing bacterial culture prior to adding substrate. The seeding with bacteria is also known as inoculum. There are various sources for seeding bacteria: digested sludge from a running biogas plant or a municipal digester, material from well-rotted manure pit, or cow dung (CD) slurry is used as seed (Yadvika *et al*. 2004). Inoculation increases biogas yield and reduces retention time, furthermore it can improve methane content in biogas (Dangaggo, Aliya& Atiku1996). It can further increase the degradation rate, shorten the starting-up period and provide a more stable digestion process (Lettinga 1996). Dhamodharan,Vikas& Ajay(2015) conducted a series of tests on the effect of different livestock dung as inoculum forFW anaerobic digestion, in their research they found that reactors inoculated with CD obtained higher methane production of 227 mL g^{-1} VS degraded and 54.58% volatile solids degradation at food to microorganism (F/M) ratio maintained at 2.

2.10.4 Feedstock

There is a wide range of acceptable, easily biodegradable biomass that could be used asfeedstock for anaerobic digestion. Feedstock in this work refers to any substrate that can be converted into biogas through anaerobic digestion. These substrates may be easily degradable or be complex high-solid waste (Roddy 2012). The success of anaerobic digestion even of toxic compounds depends on the technology applied. The main requirement from waste material is that it contains a substantial amount of organic matter that can be converted into biogas (Dobre *et al*. 2014).

Historic advancement in anaerobic technology has allowed digestion treatment of animal manure to advance to the treatment of industrial and municipal wastes even other agricultural wastes (Steffen 1998). Anaerobic digestion feedstock is mainly derived from three sources, namely agriculture, industry and community/municipality. In agriculture animal manure, energy crops, algal biomass and harvest remains are potential feedstock. In industry food/beverage processing, dairy, starch industry, sugar industry, pharmaceutical industry, cosmetic industry, biochemical industry, pulp and paper and slaughterhouse/rendering plant waste could be used. And in community/municipalityorganic fraction of municipal solid waste (OFMSW), sewage sludge, grass clippings/garden waste and restaurant and household FW may be used as feedstock (Steffen 1998).Table 2.4 outlines the characteristics and operational parameters of different feedstocks in agriculture and it can be noted that FW characteristics make it ideal for anaerobic digestion.

Table 2.4: Characteristics and operational parameters of the most important agricultural feedstocks (Steffen 1998)

Feedstock	Total Solids TS [%]	Volatile Solids [% of TS]	Biogas Yield (4) [m³/kgVS]	Retention Time [d]	CH_4 Content [%]	Unwanted substances	Inhibiting substances	Frequent problems
Pig slurry	3-8 (2)	70-80	0.25-0.50	20-40	70-80	Wood shavings, bristles, H_2O, sand, cords, straw	Antibiotics, disinfectants	Scum layers, sediments
Cow slurry	5-12(2)	75-85	0.20-0.30	20-30	55-75	Bristles, soil, H_2O, NH_4^+, straw, wood	Antibiotics, disinfectants	Scum layers, poor biogas yield
Chicken slurry	10-30(2)	70-80	0.35-0.60	>30	60-80	NH_4^+, grit, sand, feathers	Antibiotics, disinfectants	NH_4^+-inhibition, scum layers
Whey	1-5	80-95	0.80-0.95	3-10	60-80	Transportation impurities		pH-reduction
Leaves	80	90	0.10-0.30(1)	8-20	n.a.	Soil	Pesticides	
Wood shavings	80	95	n.a.	n.a.	n.a.	Unwanted material		Mechanical problems
Wood wastes	60-70	99.6	n.a.	∞	n.a.	Unwanted material		Poor anaerobic biodegradation
Garden wastes	60-70	90	0.20-0.50	8-30	n.a.	Soil, cellulosic components	Pesticides	Poor degrad. of cellulosic comp.
Grass	20-25	90	0.55	10	n.a.	Grit	Pesticides	pH-reduction
Fruit wastes	15-20	75	0.25-0.50	8-20	n.a.	Undegradable fruit remains, grit	Pesticides	pH-reduction
Food waste	10	80	0.50-0.60	10-20	70-80	Bones, plastic material	Disinfectants	Sediments, pH-reduction

1) depending on drying rate; 2) depending on dilution; 3) depending on particle size; 4) depending on retention time; n.a. = not available

2.10.5 Particle size

The particle size reduction in anaerobic digestion is the first stage carried by the hydrolysis microbes. This stage, as mentioned earlier, is one of the rate limiting stages. Therefore, it is important not to feed substrate that is too large or difficult to be broken down by microbes. Izumi, Okishio, Nagao, Niwa, Yamamoto& Toda(2010) in their experiment studied the effects of particle size reduction by ball grinding FW from 0.843 mm to 0.391 mm. They found that reducing the particle size of substrate improved the methane yield by 28%. They also found that excess size reduction led to an accumulation of VFAs that decreased methane production and solubilisation in the AD process. Smaller particles of substrate do give an increased absorption surface area for microbial activity, consequently increasing biogas production (Yadvika *et al*. 2004).

2.10.6 Solid concentration

Substrate in an AD consists of organic material in a diluted form. The degree of dilution is referred to as solid concentration and can be expressed as solids concentration or solids percentage (% solids) by total solids (%TS) or volatile solids (%VS). This is known as the mass of the TS or VS in the slurry or the chemical oxygen demand (COD) of the slurry (Thom 1994). Solids concentration variation in the substrate affects the volumetric gas production rate (VGPR) and gas yield. At low concentrations of about 4% VS, in a well-mixed digester, the VGPR was found to increase linearly with solids concentration. However, at higher concentrations, the increase in concentration had less effect (Thom 1994; Gunnerson & Stuckey 1986); this is due to the decrease in bacterial growth rate at high concentrations. Bacteria require movement to reach undigested organic material (Thom 1994). At lower concentrations, the gas yield will decrease to a certain level.

Thom (1994) reported on an observation by Hobson, Bousfield, Summers & Mills(1980) and Aubart &Fauchille (1983) that gas yield decreased with an increase in TS above 6% in experiments with pig manure and 4% in poultry excreta. Poultry excreta was found to have high levels of ammonia-nitrogen at high concentrations between 6-13% TS. Contrary to these findings, cattle manure has been digested at these concentrations without a significant decrease in gas yield (Thom 1994; Hobson *et al*. 1980; Dhawale & Danawade 1992).

2.10.7 Organic loading rate

The organic loading rate also has a major effect on biogas production rate. According to Vartak, Engler, Mcfarland& Ricke(1997), methane yield was found to increase with a reduction in loading rate. Yadvika *et al*. (2004) reported on a study carried out in Pennsylvania on a 100 m^3 biogas plant operating on manure, that a loading rate that was varied between 346 kg VS/day to 1030 kg VS/day obtained optimum loading rate at 67 to 202 kg VS/day. A feeding rate of 16 kg VS/m^3 of digester was determined by Mohanrao (1974) feeding dung produced 0.04-0.074 m^3 of biogas/kg of dung. Based on their pilot plant studies a maximum biogas yield was observed at loading rates of 24 kg dung/ m^3 digester/ day. Yadvika *et al*. (2004) established that optimum feeding rate is unique as per digester size at which maximum biogas production will be achieved, above and beyond which no more biogas yield will be observed.

According to Nagao, Tajima, Kawai, Niwa, Kurosawa, Matsuyama, Yusoff& Toda(2012), the theoretical maximum organic load for FW is 10.5 kgVS/m^3 and in their experiment they obtained the highest methane yield of 455 L/kgVS at 9.2 kgVS/m^3/day. Overall methane yields were 417, 421, 444, 455 and 432 L/ kgVS with OLRs of 3.7, 5.5, 7.4, 9.2 and 12.9 kgVS/ m^3/ day, respectively.

2.10.8 Agitation

A homogeneous mixture of substrate promotes successful digestion as microorganisms and substrate will be distributed throughout the reactor, which prevents local buildup of concentrated intermediate metabolic products that can slow down methanogensis. Agitation can be achieved in various ways: feeding daily can give an adequate mixing effect, mixing can also be achieved by installation of stirring mechanisms such as scraper, piston and a pump and biogas recirculation has also been found to be effective for mixing and improving biogas production (Mohanrao 1974; Aubart & Farinet 1983; Van & Faber 1996; Yadvika *et al*. 2004).

2.11 Types ofpilot anaerobic digesters

There are different types of digester designs,however, they all perform the same basic function. They hold organic matter in the absence of oxygen and maintain suitable conditions for methanogens to grow (Hamilton 2019).These digesters perform this basic function is different ways, nevertheless. The selection of a digester design is influenced by the technical suitability, cost-effectiveness and the availability of local skills and materials. Furthermore, design selection is influenced by prove design in the region for the range of feedstock which in turn depends on the climatic and economic conditions (Vögeli *et al*. 2014).

The four main types of digesters employed commonly in developing countries such as South Africa for wet mesophilic digestion of high solids waste are the plug plug-flow, fixed-dome, floating-drum and complete-mix digesters. These digesters are generally inexpensive, built with locally sourced material, easy to handle, have few moving parts and are thus less susceptible to failure.Anaerobic digestion has been in use for over 80 years and this shows how viable technology is. However, problems arise when there are limitations in capital and operational skills (Gunnerson and Stuckey 1986).

2.11.1 Plug flow digester

The plug flow digester consists of anelongated longitudinal shaped, heat-sealed and weather resistant plastic or rubber tube that stores both digestate and biogas (Vögeli *et al.*2014). The lower part of the tube stores digestate and the upper part biogas.The vessel is typically five times longer than its width (Ramatsa, Akinlabi, Madyira& Huberts2014).The inlet and outlet of affluent and effluent, respectively, are attached directly to the membrane of the tube on opposite ends of the tubular structure.When new feed is added to the digester, it pushes existing digestate to flow through the digester in a plug-flow manner (Ramatsa *et al.* 2014). The mechanism is however more complicated than that, some parts of the existing digestate travel faster than others on their way through the digester while others settle/float and remain in the digester (Hamilton 2019).The digester has minimum active mixing as there is typically no mixing device in this type of a digester (Vögeli *et al*. 2014). The biogas outlet is attached directly to the membrane of the tube to the very top of the digester as depicted inFigure 2.4. When biogas is produced and the gas space is full, the tube becomes inflated and when there is no biogas in the digester the tube becomes deflated and rests on the digestate liquid surface(Sasse 1988). Biogas pressure can be increased by placing weights on the tube.

The plug-flow is commonly placed in ground for improved insulation and protection against mechanical damage, the shallow below ground installation makes the plug flow most suitable for areas with a high groundwater table (Vögeli *et al*. 2014). Due to its low cost of construction, simple technology and installation, this model has been rapidly adopted and disseminated to farmers (Bui, Thomas& Frands1997). This digester type is not very insulative and is thus most suitable in regions where the climate is warm. It has a short life span of 2-5 years due to its material of construction that is fragile and susceptible to ultraviolet and mechanical damage (Nzila, Dewulf, Spanjers, Tuigong, Kiriamiti & van Langenhove2012).Its lifespan can be increasedby installingthe digester in a sheltered area away from direct sun radiation but still allowing for sun heating. Further barricadearound the digester can be used to prevent mechanical damage from large moving objects such as trucks and animals(Vögeli *et al.* 2014). The first documented use of the plug-flow was in South Africa in 1957 (Singh, Myles & Dhussa 1987).

The plug flow digester has been improved over the years in terms of mixing,construction material and heating/insulation. An external mixing grinder pump could be used to agitate the digestate through PVC pipe connections (Puxin Technology 2017). The digester could be heated by constructing a greenhouse structure over the digester, this also adds insulation during colds temperatures(Puxin Technology 2017). Materials such as PVC tarpaulin have now been successful in digester construction. PVC tarpaulin is resistant to UV, oxidation, chemicals, corrosion, tear, isfire retardant and have excellent tensile strength, anti-stripping properties and good wear resistance. This gives it a life span ofmore than 10 years(Gaiatarp 2020).

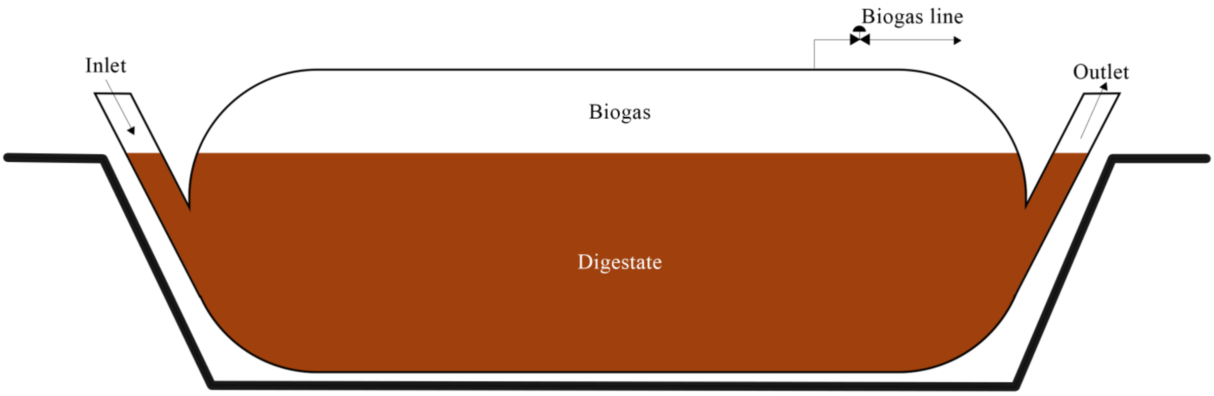

Figure 2.4: A schematic representation of a plug-flow digester (Hamilton 2019)

2.11.2 Fixed-dome digester

A fixed-dome digester comprises of a closed, immovable top reactor in the form of a dome. The digester contains both digestate and biogas, residing on the lower and upper area, respectively, as outlined in Figure 2.5. The digester has an inlet pipe for feed stock and a displacement pit, also known as the compensation tank (Vögeli *et al*. 2014). The displacement pit serves for effluent discharge and biogas pressure regulation.On a closed biogas outlet valve pressure, biogas in the digester builds up and displaces an equivalent amount of digestate into the pit, when the gas valve is opened the liquid in the pit createsa back pressure in the digester pushing out the biogas that displaced it (Vögeli *et al*. 2014). Therefore, biogas pressure increases with biogas production and decreases with biogas use. Owing to this designmechanism,internal biogas pressure varies continuously depending on biogas production and use, furthermore biogas production should not exceed the size of the compensation tank. To obtained constant pressure an external floating gasholder or a balloon biogas storage may be installed (Sasse 1988). This type of a digester was built in China as early as 1936 (Biogas SA).

The fixed dome is commonly constructed with bricks, concrete or quarry-stone masonry and then plastered. This requires a skilled technician to ensure a water and gas tight construction. The underground placement of the digester helps with insulation from cold weather temperatures at night and during winter (Vögeli *et al*. 2014).

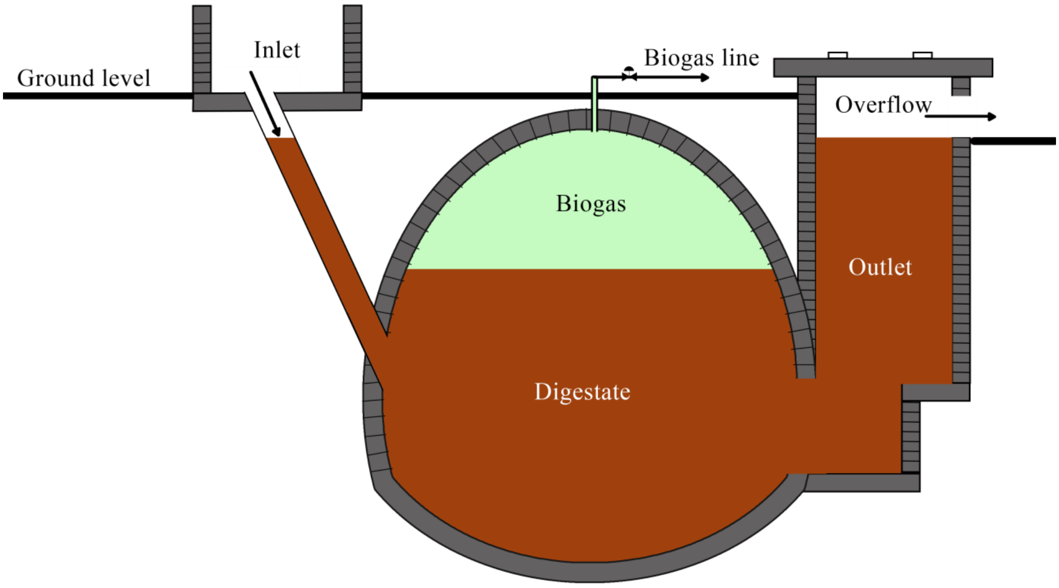

Figure 2.5: A schematic representation of a fixed-dome digester (Vögeli *et al*. 2014).

2.11.3 Floating-drum digester

A floating-drum digester consists of anopen topreactor,covered by a floating gasholder (drum). The gasholder floats either directly on the digestate or a water jacket of its own.The digester is typically constructed underground and the gasholder remains above ground (Vögeli *et al*. 2014).Produced biogas is collected in the drum, which raises it. When biogas is withdrawn, the drum falls again. The drum level provides a useful visual indication of the amount of biogas available.A guiding pole or frame can be constructed on the inside or outside, respectively, of the drum to avoid tilting of the drum when it rises as illustrated in Figure 2.6. Biogas pressure is relatively constant and regulated by the weight of the drum, additional pressure can be obtained by adding weights to the top of the drum. Mixing can be achieved by adding braces to the inside of the drum that can agitate the digestate whenthe drum is rotated. An experiment on the floating drum in India began in 1937 (CARE 2020)

The digester of the reactor is commonly constructed with bricks, concrete or quarry-stone masonry and then plastered. The floating drum is typically made from steel and is coated with bitumen, oil or synthetic paints to protect it against corrosion (Sasse 1988). Further de-rusting is necessary for a sustained use and the cover coating should be applied annually. A well-maintained metal drum can have a life span of 3-5 years in humid areas and 8-12 years in dry areas.Other materials have been used; glass-fibre reinforced plastic, polyvinyl chloride (PVC), high density polyethylene (HDPE), linear low-density polyethylene (LLDPE) have been used successfully (Sasse 1988). Wire-mesh-reinforced concrete are intrinsically porous and are liable to hairline cracking, thus require gaslight, elastic internal coating. Glass-fused-to-steel (GFS) has become the most popular nowadays due to its low capital cost in comparison with concrete, itprovides optimum corrosion resistance and it has a lifetime coating; re-application is thus not required reducing operational costs and downtime (Permastore 2020).With GFS the gas holder is flexible and made from PVC tarpaulin or HDPE flexible sheet. This modified digester is referred to a complete mix tank.

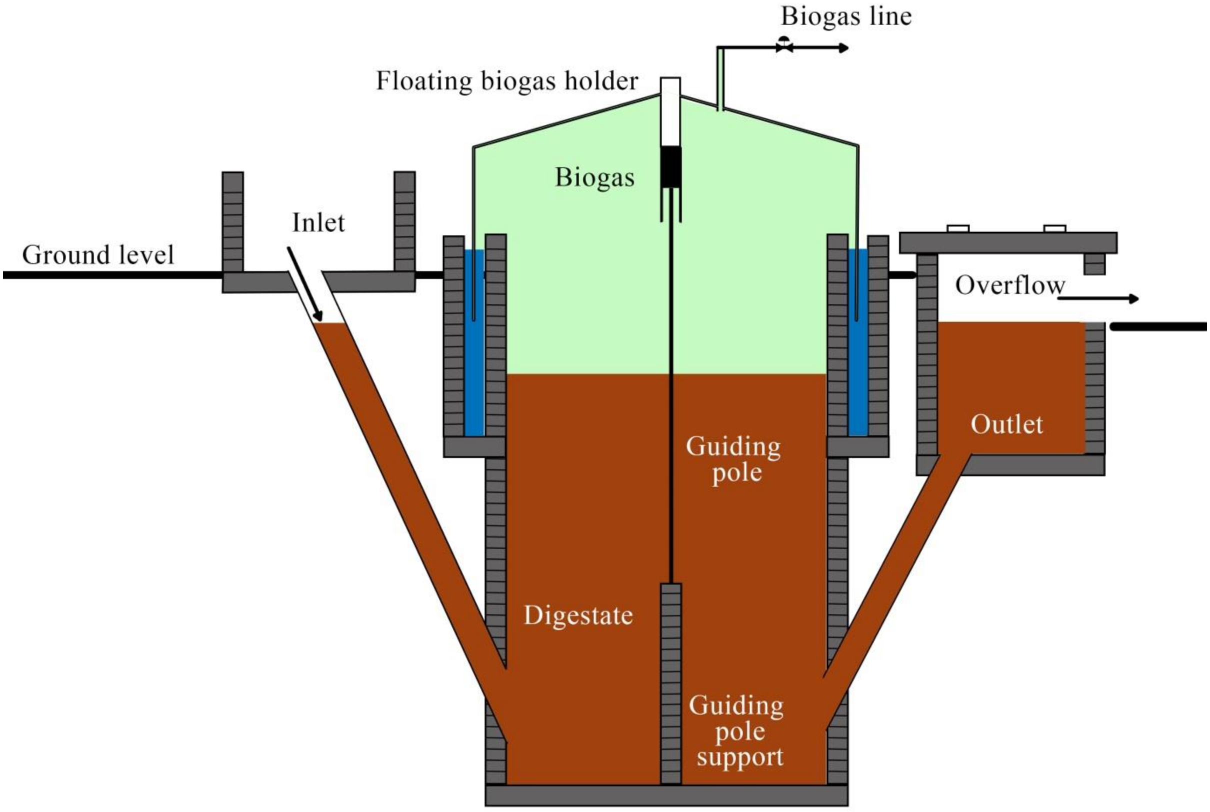

Figure 2.6: A schematic representation of a floating-drum digester (Estoppey 2010 cited in Vögeli *et al.* 2014, p36).

2.11.4 Complete mix

A complete mix tank digester is a cylindrical tank with a rigid or flexible cover (Chen & Neibling 2014).Figure 2.7 demonstrates a flexible cover complete mix digester.Rigid top digesters store biogas in an external floating drum or biogas balloon. The digester receives consistent heating and mixing. The operating temperature can be in either the mesophilic or thermophilic range. The mixing of the digester can be either continuous or intermittent. The complete mix digester iscommonly made from GFS.The tank would then be insulated with mineral wool that is covered with corrugated iron sheets to protect against the weather. When new feed is added to the digester, an equal amount of digestate is removed in order to maintain a desired liquid level. Sometimes digestion takes place in more than one tank. For instance, acid forming bacteria break down organic matter in one tank and methanogens convert organic acids to biogas in a second tank (Hamilton 2019).

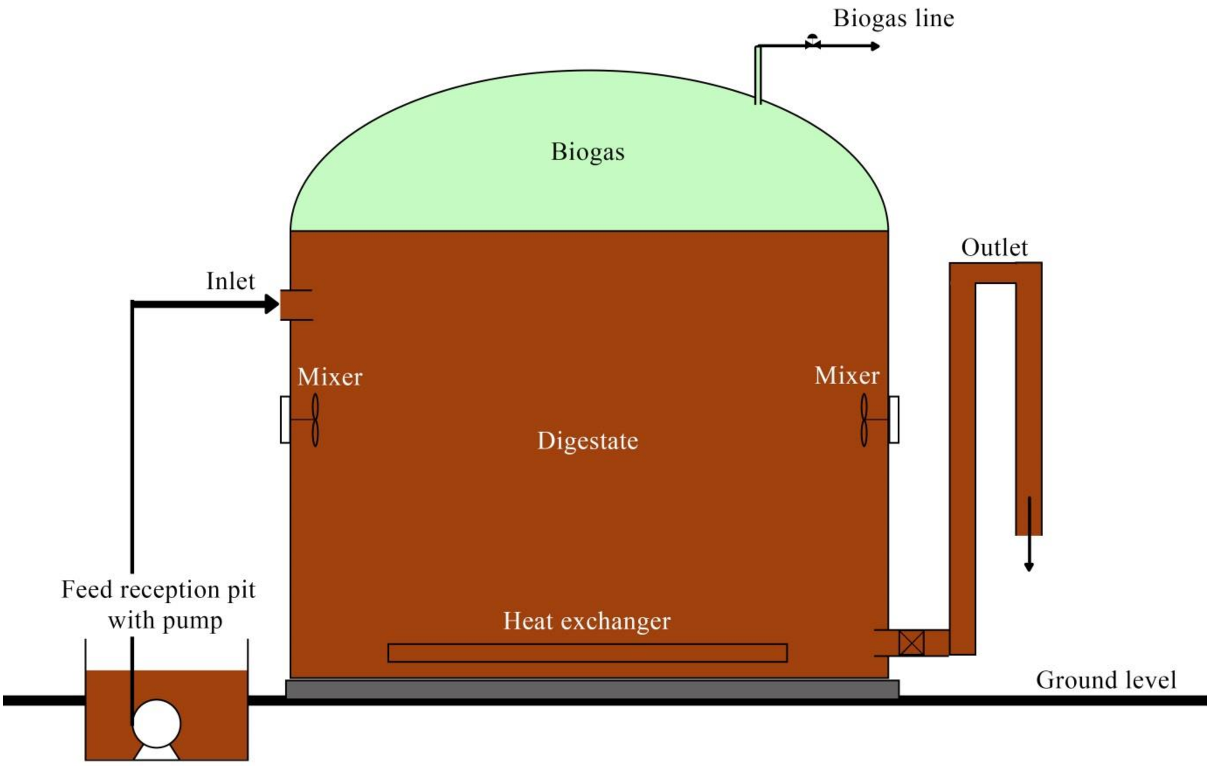

Figure 2.7: A schematic representation of a complete mix digester (Chen & Neibling 2014)

2.12 Kinetic modeling of anaerobic digestion

The mathematical kinetic models used for the AD process are vital in predicting, monitoring, optimising and simulating process performance under various conditions (Bong, Lim, Lee, Ho & Klemes 2017). Additionally, the models assist in the understanding of the digestion process and prediction of kinetics parameters (Otieno 2020; Yetilmezsoy 2012). Deepanraj, Sivasubramanian & Jayaraj (2017) compared two kinetic models namely the modified Gompertz model and the Logistic model to determine the kinetics parameters of the AD of FW under different total solid (TS) concentrations. In their findings, the modified Gompertz model yielded better performance and provided a better description of the process kinetics compared to the logistic model.

2.12.1 Kinetics of biogas production: Modified Gompertz equation

The modified Gompertz model commonly describes the cumulative biogas production during anaerobic digestion and has proven to be an excellent empirical non-linear regression model (Kafle & Chen 2016; Zahan, Othman & Muster 2018) The model describes the cell density during microbial growth periods in terms of exponential growth rates and lag phase duration (Pramanik, Suja, Porhemmat& Pramanik 2019). Moreover, the model assumes that the biogas production rate by the methanogens corresponds to the specific growth rate. The equation is given by:

$$\boldsymbol{B_t = B_p exp\left\{-\exp\left[\frac{R_b e}{B_p}(\lambda - t) + 1\right]\right\}} \quad \textbf{(2.1)}$$

where, B_t, B_p, R_b, and λ are the cumulative biogas produced (L) at a given time, biogas production potential (L), maximum biogas production rate (L/hr), and the lag phase (hrs). The lag phase is the duration taken before biogas production starts after feeding.

2.13 Anaerobic digester design

According to Mukumba *et al.* (2016), one of the contributing factors to the failure of household digesters is due to underfeeding of digester caused by the unavailability of appropriately-sized digesters; digesters found on the market had one particular size that did not fit all applications; thus, adequate sizing is critical. The installer needs to know the amount of waste available on a daily basis and optimum solids concentrations for the type of waste and how much biogas potentially can be produced from the waste material. This will give an indication on the adequate size of both the digester and gas holder.

Furthermore, high investment is typically required in the construction of a proper working digester structure. In recent years, there have been great technological advancements that have made available a variety of strong low-cost materials that are suitable for digester construction. Materials such as PVC and PE have been made more durable and available in various forms.

2.14 Biogas purification

Biogas mainly consists of three contaminants: hydrogen sulphide (H_2S), carbon dioxide (CO_2) and free moisture (H_2O). The main contaminant in biogas is H_2S that is responsible for the bad smell in biogas and corrosion in end use application (Pipatmanomai, Kaewluan& Vitidsant2009). Raw biogas is ready for use only in terms of heating content. H_2S presents ranges from 50-10 000 ppm depending on substrate composition used for digestion. Within this range, H_2S can cause corrosion to engine and metal parts via SO_2 emissions from combustion, particularly when the engine is working on a batch basis and the workplace can be intoxicated with H_2S/SO_2. This presents high maintenance costs on combustion equipment and health hazards in the workplace. As a result, it is critical to remove H_2S prior to utilisation (Pipatmanomai *et al*. 2009).

H_2S removal technologies have three categories, namely (a) absorption into a liquid either water or caustic solution, (b)adsorption on a solid such as iron oxide based materials typically iron sponge, activated carbon or impregnated activated carbon and (c)biological conversion by which sulphur compoundsare converted into elemental sulphur by sulfide oxidising microorganisms with addition of air/oxygen (Pipatmanomai *et al.* 2009). Another method adds 2 to 6%air to the digester headspace that oxidises H_2S in biogas into sulphur. The most feasible method should be selected for operation.

2.15 Biogas conversion to electricity

One of the first commercial anaerobic digesters to produce biogas and generate electricity from it in South Africa was by John Fry in 1957 at his pig farm (Mother Earth News 1973). Currently in South Africa, there are about 300 different sized operating biogas plants accounted for and more need to be taken into account. Johannesburg Waters (JW) municipality based in Gauteng has four working anaerobic digesters to reduce the total organic load on their plant and to stabilise the sludge before disposal. They are producing approximately 2 million m^3/yr of biogas from wastewater sludge. WEC Projects is running a set of two generators, each having a power output of 300kW and instantly feeding approximately 5 MW electricity a year to the grid. Bio2watt in Bronkhortspruit, South Africa, is running a 4.6 MW biogas power plant from about 120 000 tons per year of organic waste from a Beefcor Farm. Companies such as Botala Energy Solutions and Biogas SA can be hired to install small- to large-scale plants around South Africa. Ysar, Ali, Tabinda & Tahir(2014) reported that a biogas power plant at Shakarganj Sugar mills in Pakistan produced 20.34 million m^3 of biogas from 0.5 million m^3 of spent wash, giving a total electricity production of 37.7 million kWh. The electricity production efficiency of 92% was reached using a new biogas boiler. Mydin, Nik Abllah, Md Sani, Ghazali & Zahari(2014) report that from 1000 kg of FW from canteens and cafeterias, they were able to produce 180 m^3 of biogas per day and generate 600 kW of electricity per day from their mini biogas plant used in Malaysia at Universiti Sains Malaysia.

South Africa produces 9 million tons of FW per annum. This amount of FW can produce a significant amount of biogas. The biogas potential of this FW can be calculated using equations2.1 and 2.2.These equations predetermined biogas yields from previous research work to predict the biogas potential. For 9 million tons of FW per annum an anaerobic digester operated at mesophilic optimal conditions the biogas yield (BY) from Xu*et al.* (2018) was found to be879 L/kgVS$_{added}$. In 9 million tons of FW,volatile solidsVS is assumed to be 95% and TS15%; thus, total VS (TVS)available would be 1 460 234 kgVS. Total biogas potential is 1 283 546 169L.

$$TVS = (FW * TS\%) * VS\% \tag{2.1}$$

$$E_{biogas} = BY * TVS \tag{2.2}$$

Biogas can be converted into electricity through small and large combustion engines. Larger engines have a combined heat and power capacity to provide heat to the anaerobic digester and other processes. Typically,small engines have a conversion efficiency of 25% and 35 to 40% for larger engines (Nielsen 2002 and Tafdrup 1995)

In this analysis, engine conversion efficiencies of 25 and 40%are used to predict energy potential for small- and large-scale electricity generation, respectively. Equation 2.3 was used with the conversion efficiencies to determine the electricity potential from the biogas.

$$e_{biogas}[kWh] = E_{biogas}[m^3] * 22\ [MJ/m^3] * 0.277778\ [kWh/MJ] * \eta \qquad (2.3)$$

where,e_{biogas} represents the total electricity that can be generated from biogas in kWh, E_{biogas} is the unconverted rawenergy in the biogas in m^3, 22 MJ/m^3 is biogas calorific value assuming 60% methane, 0.277778 kWh/MJ is a unit conversion from MJ to kW and η is the generator's overall conversion efficiency.

From 1 283 546 169 L of biogas 1 960 and3 137 MWh of electricity at 25 and 40% conversion, respectively, can be generated from South Africa's current FW, which is enough to turn on 326 and 522 million 6W light bulbs per hour, respectively.

Even though biogas in South Africa was first produced in the 1950s (Mukumba *et al.* 2016) the use of it remains very low. Mukumba *et al*. (2016) reported that this is attributed to the lack of research work on biogas technology and purification processes, leading to low efficiency of biogas as compared to conventional fuels such as diesel and petrol, cheap electricity cost from coal-fired thermal power stations, education and awareness on biogas in general and funds to startup and maintain a digester. One of the main challenges reported on biogas development in South Africa is the lack of a generic solution to run a digester. Most of the data available are based on other countries' research and cannot be used directly in South Africa. Thus, more South African anaerobic digestion research needs to be conducted to promote biogas utilisation locally (Mukumba *et al*. 2016).

2.16 Conclusion

The literature review section outlined the quantities of FW in the food sectors and showed that the characteristics of FW has previously proved to be highly biodegradable and suitable for anaerobic digestion. The uncontrolled disposal of FW has shown to have a negative impact on the environment. The treatment of FW through anaerobic digestion produces biogas, a renewable energy, which can be used for cooking and generating electricity.

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CHAPTER 3: METHODOLOGY

The pilot biogas plant was designed and constructed using locally-sourced materials. The newly constructed plant was commissioned with water and ensured to be gas-tight. Cow dung (CD) was bought from a local farm and characterised upon receipt. The characterisation studies were carried out to determine pH, moisture content, total solids and volatile solids. The CD was then used to inoculate the digester with methanogenic bacteria and was consequently pre-incubated until biogas production halted. The effect of organic loading of kitchen food waste (FW) was then determined using different organic loads while monitoring the biogas production, biogas quality, digestate pH and digester temperature. Using the optimal organic load, the digester was operated for 35 days and the generated biogas was used for generation of electricity. The biogas potential and system design of the complete mix digester was compared to that of a plug-flow digester operated at the manufacturer's optimal organic load at a local restaurant. The plug-flow digester was used to provide additional data and to evaluate the feasibility of the pilot-scale complete mix digester design. The energy balance of the pilot plant was calculated to determine the efficiency of the system. The total energy produced per day was used to estimate the system's energy potential to power South African household light bulbs when applied on a larger scale.

3.1 Materials

A locally-made Jojo tank (1000 L), clear pipe of 8 mm internal diameter, high-density polyethylene (HDPE) pipe, PVC tarpaulin, fittings, solar geyser, insulation material, biogas compressor, submersible grinder pump, pH meter (Hanna model: HI 9813-5) and plexiglas floating drum were purchased at local hardware stores. Digester construction materials were assembled at the Vaal University of Technology (VUT). The 1.5 kW biogas generator was purchased from Puxin Technology, in China. A handheld biogas analyser was purchased in China, Beijing Shi'An Technology Instrument Co., Ltd. A Ritter biogas meter was donated by Devos Laboratory. Cow dung (CD) was sourced from a local farm in Vanderbijlpark and FW was collected from the VUT Vanderbijlpark campus cafeteria. FW comprised of mainly organic materials including rice, slap chips, buns, bread, porridge, grease, raw dough, chicken, meat, vegetables and fruits. Idwala Industrial Holdings (Pty) Ltd, lime distributors, donated 20 kg of slaked lime.

3.2 Experimental setup

The experimental setup consisted of complete-mix (VUT-1000C) and plug-flow (STH-1000A) anaerobic digesters operated at a controlled temperature of 37 ^{o}C and ambient temperature, respectively. VUT-1000C was designed and constructed from a 1000 L vertical Jojo tank with a working volume of 800 L. A gas holder was made from PVC tarpaulin and a floating drum from plexiglas to measure the amount of biogas produced. The substrate was mixed using a submersible 180 W grinder pump. The digester was heated using a 100 L solar geyser equipped with 15 vacuum tubes and a temperature controller. A thermocouple was inserted inside the digester and connected to a temperature controller, which turned the hot water circulation pump on and off to maintain the desired digester temperature. The digester was insulated from cold winds by wrapping with insulation glass wool. The glass wool insulator was covered with a double-sided foil-reflective insulator for protection against harsh weather conditions. STH-1000A was constructed from a PVC tarpaulin balloon with a working volume of 600 L. The digester was covered in a greenhouse structure for heating and insulation. A floating drum was used to store produced biogas.

A food blender was used to reduce the particle size of FW. Excess pressure relief was achieved by a water seal created by submersing the biogas line outlet into 40 mm of water (40 mmwc ≈ 400 Pa). Biogas quantity was measured with a biogas meter, with a flow rate ranging between 1 and 18 000 L per hour. Biogas composition was analysed and measured using an online natural diffusion hand-held biogas analyser, pH using a pH meter and temperature using a temperature controller connected to a thermocouple. An 18 W biogas compressor was used to extract biogas from the biogas holder to supply to downstream processes. A 1.5 kWh generator was used for electricity generation with a conversion efficiency of 22%. The experimental setup is outlined in Figure 3.1.

3.3 Design and assembly of the complete-mix biogas pilot plants (VUT-1000C) and design outline of the plug-flow (STH-1000A) digester

In this study, a complete-mix biogas pilot plant (VUT-1000C) was designed, assembled and commissioned at the Vaal University of Technology, Vanderbijlpark (see Figure 3.1a). The plug-flow 1 m^3 digester (STH-1000A) was purchased from China by Devos Laboratory to showcase biogas technology in South Africa at Stonehaven, a popular restaurant in

Vanderbijlpark (see Figure 3.1b). VUT-1000C was chosen to be an above-ground complete-mix digester because it was the most suitable for this application; it offered much flexibility during experiments and ease in maintenance. The design and commissioning aspects of the digester design are discussed in detail in this section, while the plug-flow digester design is outlined. The biomethane potential of different waste foods was evaluated through the complete-mix digester, while the plug-flow was operated at the manufacturer's specified optimal organic load.

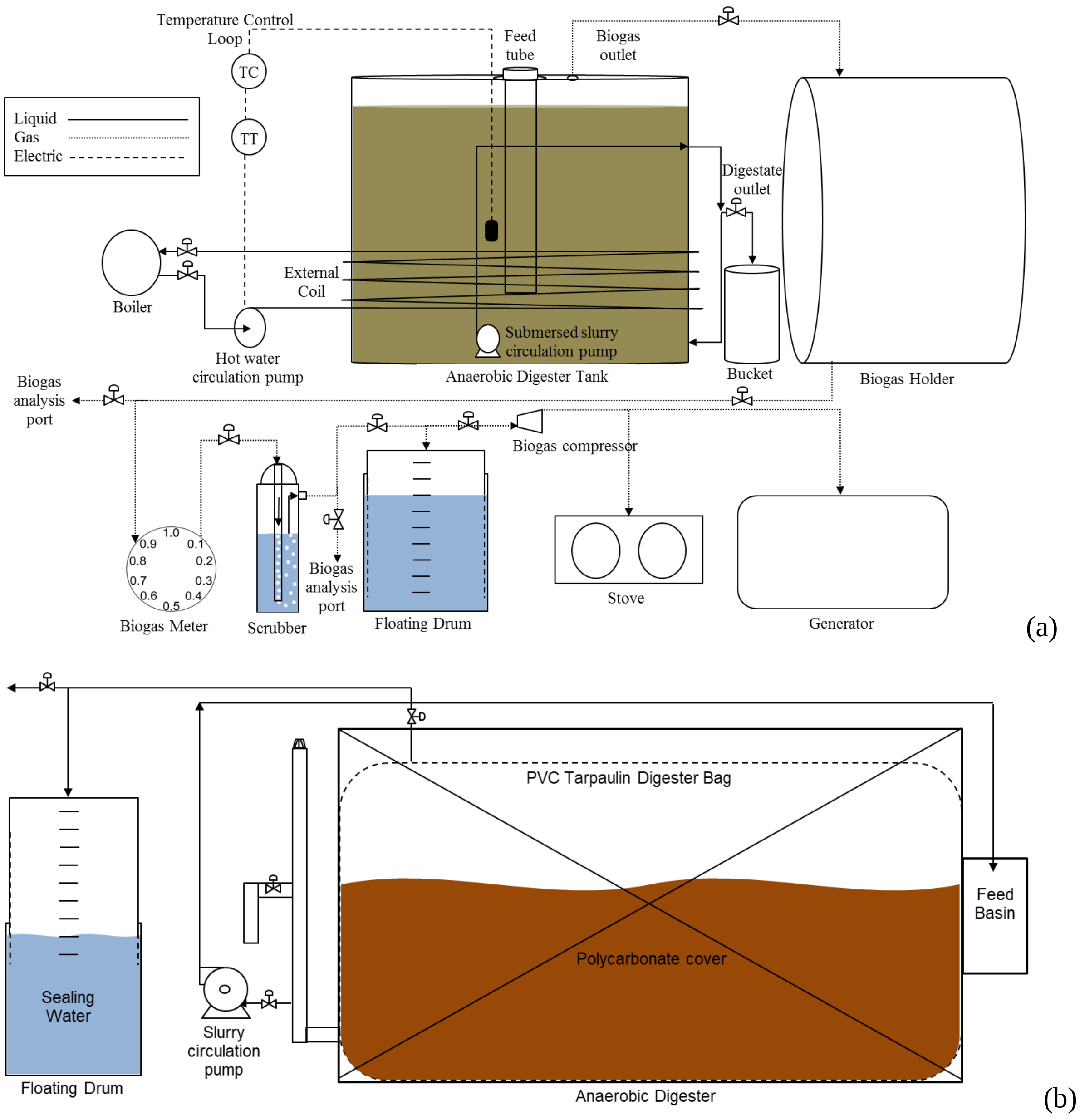


Figure 3.1: Schematic representation of (a) VUT-1000C biogas pilot plant coupled to an electricity generator and (b) STH-1000A digester

3.3.1 Reactor material of construction

The 1 m^3 pilot complete-mix reactor vessel was chosen to be an above-ground digester with a prefabricated tank to reduce special installation and fabrication costs. A heavy-duty chemical-grade linear low-density polyethylene (LLDPE) tank made by Jojo Tanks was found suitable for this application. The tank was 1000 L in capacity, with a diameter of 1.11 m and a height of 1.3 m, a wall thickness of 5 mm for contents with a specific gravity (SG) of 1.6. The wall thickness offers a long life span for the reactor under heavy chemical conditions for more than 10 years (Jojo Tanks 2016). LLDPE has a high tensile strength and offered good resistance to chemicals and mild to strong buffers (Omnexus 2016). The reactor tank was readily available and had a relatively low purchase cost; it was purchased off the shelf at a local hardware store. The availability of this tank reduced the overall costs for assembling the pilot plant significantly.

Similarly, the STH-1000A was designed to be an above-ground digester for easy installation. The STH-1000A plug-flow digester's reactor vessel membrane was made from PVC tarpaulin. PVC is a low-cost material and has physical properties suitable for anaerobic digestion application and has been widely used in tubular plug-flow digesters (Sasse 1988). The PVC tarpaulin used was of high quality to ensure a 10-year life span for the digester reactor. This digester has the same capacity of 1000 L as VUT-1000C. It has a width of 0.83 m, length of 1.21 m and height of 1 m.

3.3.2 Heating Method

Complete-mix digesters commonly have an external heat exchanger that supplies heat to the digester (Krich, Augenstein, Batmale, Benemann, Rutledge & Salour2005), while plug-flow to tubular digesters are commonly operated at ambient temperatures (Krich *et al*. 2005). The VUT-1000C design was equipped with an external boiler, a solar-heated geyser, with no electrical back up element; its properties are listed in Table 3.1. The boiler was connected to a heating coil placed on the outside wall of the tank. The coil was placed on the outside of the tank for maintenance reasons. The heating coil was made from 15 mm high-density polyethylene (HDPE), class 4 piping that has a good low heat resistance, which made it excellent to transfer heat to the reactor (Omnexus 2016). The digester tank, along with the heating coil was covered with two layers of insulation; the inner layer was a 40 mm glass-wool thermal insulator and the outer layer was a reflective aluminium insulative sheet. The aluminium sheet protected the inner glasswool from weathering. The glass wool and aluminium sheet had r-values of 0.7 and 1.57, respectively.

Table 3.1: Heat exchanger properties

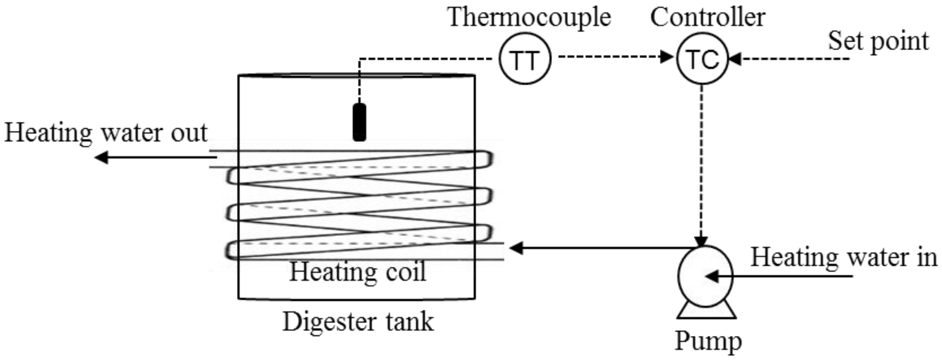
Parameter	**Value**
Type of geyser	Solar Water Heater
Hail & Freeze Resistant	Yes
Cover/Tube Material	2.0 mm Thick Glass
Water container capacity	100 L
Heat Transfer Method	Direct
Circulation Method	Thermosiphon
Installation Orientation	Horizontal
Wall or Floor Mounting	Floor
Energy Rating for Standard Day	14.2 MJ
Overnight Energy Losses	7.80%
Aperture Area	0.975 m^2
Hail Cover Required	No

The boiler chosen was a 100 L solar geyser with 15 vacuum tubes. The geyser had an energy rating of 14 MJ/day. With this daily energy rating, the geyser could heat 800 L of water from 25 to 37 ^{o}C in at least 4 days with overnight energy loss of 7.8%. The solar geyser used a 5 W temperature and water level controller that regulated the two parameters, as set by the operator's specification and safety limitations. A hot water circulation pump was connected between the boiler and heating coil to circulate the hot water. The external heating coil of the digester is represented graphically in

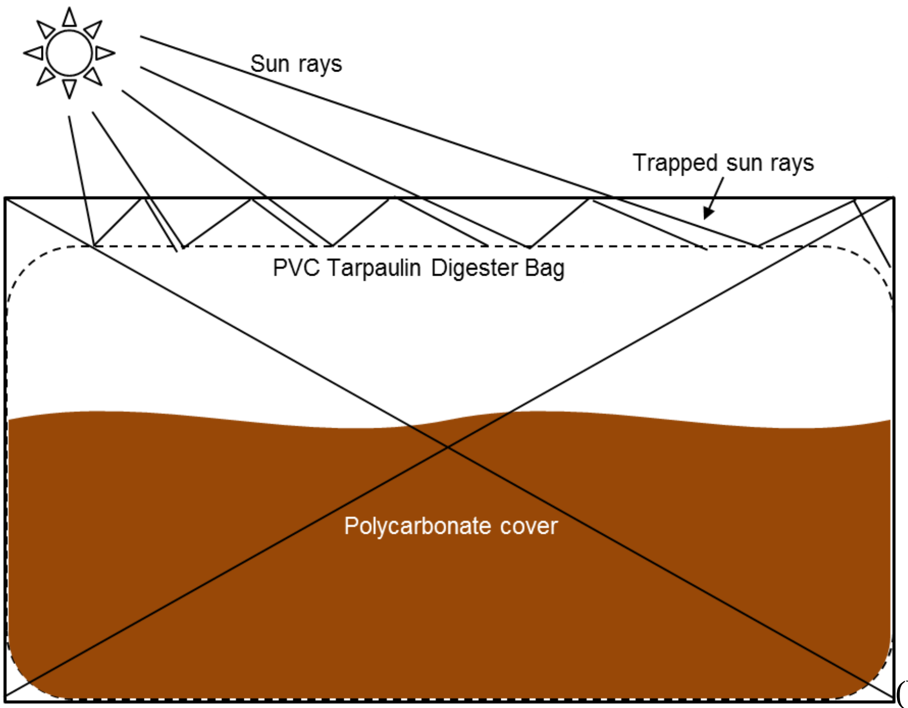
Figure 3.2a.

The plug-flow digester was enclosed in a greenhouse structure to enhance solar heating during sunny days and provide some insulation during cold periods (Puxintech 2016). The design of the greenhouse was that of a hoop design. It was framed with galvanised steel square tube and covered with polycarbonate sheeting. The greenhouse structure had a width of 0.83 m, length of 1.21 m and an arc extending 0.20 m above the vertical wall, giving an overall height of 1.30 m. Polycarbonate allows sun rays to pass through it and converts them into heat energy. The heat energy requires more time to pass through the polycarbonate material thus resulting in a temperature increase in the internal environment of the structure (Taki 2018); this principle is illustrated in

Figure 3.2b. Thus, the digester operated at enhanced ambient conditions.



(a)



(b)

Figure 3.2: Schematic representation of (a) VUT-1000C cascade temperature control system and (b) STH-1000A polycarbonate trapping sun rays as heat

3.3.3 Temperature control system

A temperature control system was installed to monitor temperature variations in the digester. The controller consisted of a thermocouple, digital module and hot water circulation pump. The digital module and hot water circulation pump had a power rating of 3W and 8W, respectively. The hot water was circulated at a rate of 38 L/min. The thermocouple was placed inside the digester towards the centre to give an accurate reading of the internal temperature, away from the sidewalls of the tank where the heat was received. The controller was connected to a hot water circulation pump that implemented the temperature adjustment commands.

The cascade temperature-control system applied in this experiment is illustrated in

Figure 3.2. The controller received a setpoint from the operator, measured the temperature inside the digester, then turned the hot water circulation pump on or off to make temperature adjustments. When the temperature in the digester was below the setpoint, the controller turned on the pump to circulate hot water until the temperature in the digester rose to the set temperature. After reaching the set temperature, the controller turned off the pump. The controller was given a 0.3 ^{o}C deviation range, meaning when the temperature dropped 0.3 ^{o}C lower than the setpoint, the controller kept the pump turned off. Outside this range, the controller turned the pump on. The heat exchanger was set to 20 ^{o}C higher than the digester desired temperature to avoid temperatures in the digester escalating beyond the set range; thus, requiring a cooling system. STH-1000A did not have a temperature control system as it operated at ambient conditions.

3.3.4 Mixing

In a complete mix anaerobic digester, there are three types of mixing, which include mechanical, gas and pumped (jet) (Krich *et al*. 2005). The VUT-1000C digester used jet mixing by utilising a submersible grinder pump to circulate the digestate internally. The pump sucked in the slurry from the bottom of the digester and jetted it to in two portions. The first portion of the fluid was sprayed at the brink of the fluid to break the solid layer that typically forms due to light particles floating up and the second was jetted at the bottom of the tank to agitate settling particles. This created a swirl effect as depicted in Figure 3.3. The mixing pump had a timer that turned it on hourly for 15 minutes and operated at a flow rate of 200 L/min.

The jet mixing was also used in STH-1000C, however, the digestate was circulated using an external pump as depicted in Figure 3.4c. The external pump recirculated digestate from the digestate outlet pipe and poured it into the feed basin. The use of an external pump was due to the flexibility of the digester membrane material requiring minimum in-basin moving parts, which made maintenance easier. A 0.45 kW pool pump was used for this application yielding a 120 L/min flowrate. The pumps original impeller was replaced with an open vein impeller to prevent sludge build-up resulting in pump blockage. The mixing pump, likewise, had a 15 minute timer.

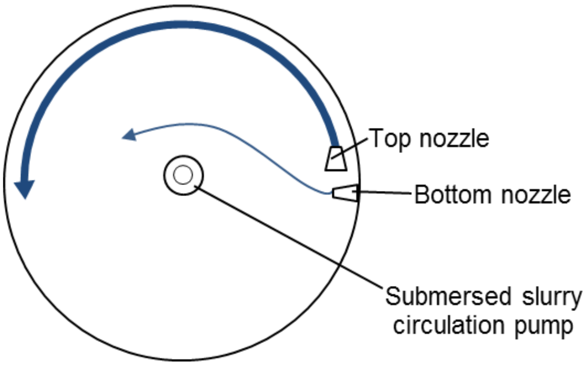


Figure 3.3: Representation of fluid flow in the digester during pump mixing

3.3.5 Feeding

The digester was fitted with a 100 mm diameter feeding tube. The tube was positioned at the centre and extended two-thirds towards the bottom of the tank, as illustrated in Figure 3.4a. At this level, the tube was submerged in the digestate creating a water seal so that no biogas escapes during feeding. FW was crushed before feeding, which was achieved by using a waste food grinder of 373 W. The crusher was installed onto a basin standing alongside the digester as depicted in Figure 3.4b.

Unlike VUT-1000C feed tube, STH-1000A used a feed basin located on the front end of the digester, as illustrated in Figure 3.4c. The feed basin was made from stainless steel sheeting and was 0.52 m high, 0.20 m wide and 0.30 m long. The feed basin position made it easy to monitor the digestate liquid level. The stainless steel material is very good at resisting chemical corrosion and also hygienic as it is easier to keep clean (SASSDA 2017). The PVC piping used to carry the effluent was resistant to chemical corrosion and had UV protection for a longer lifespan (Sasse 1988).

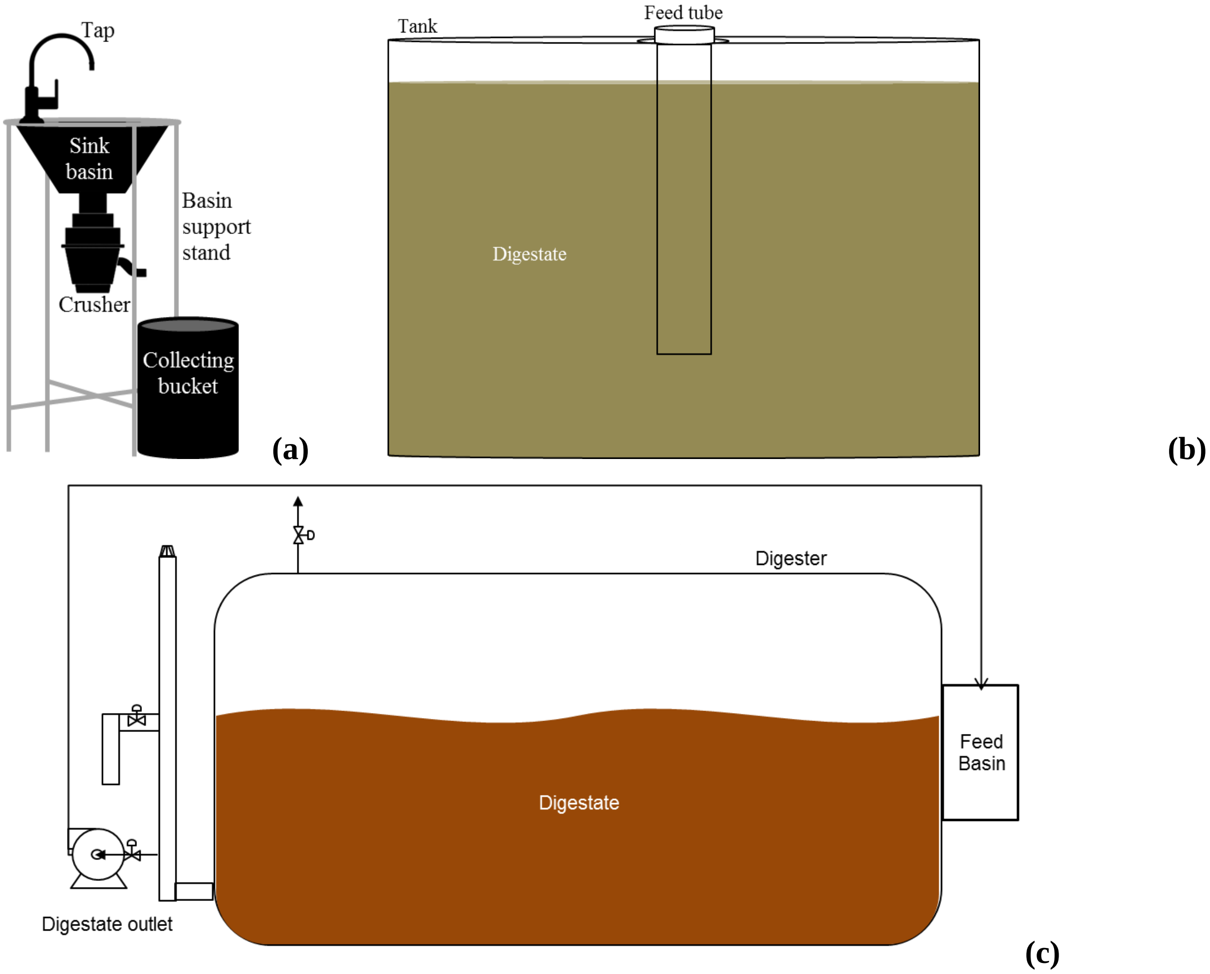


Figure 3.4: Schematic representation of the (a) food crushing basin and (b) VUT-1000C feed tube and (c) STH-1000A feed basin and digestate mixing

3.3.6 Gas handling

Produced biogas from the digester was transferred to downstream processes using an 8 mm diameter clear pipe for VUT-1000C and an opaque pipe for STH-1000A. The gas pipe connected the plant reactors allowing the biogas to pass through different treatment processes. The clear pipe allowed for visual monitoring of water condensation accumulation in the pipeline, as these tend to block the pipeline in low pressure digesters (Lusk, Wheeler & Rivard1996). STH-1000A had an inline dehumidifier,whereas,in the case of VUT-1000C any water condensation found in the pipeline was manually removed. Produced raw biogas passed through a biogas flow meter, scrubber, holder, floating drum and compressor and further on to the electricity generator and biogas stove.

3.3.7 Biogas measurement and analysis

Biogas quality and quantity were measured and analysed, respectively, before utilisation. The same technique was used for both digesters. The Ritter biogas meter installed measured the quantity of biogas produced in litres and millilitres. Its flowrate was from 1 to 18000 L per hour, using the principle of a rotating counting wheel and displacement. The biogas meter contained a revolving measuring drum within the water. The measuring drum compulsorily measures volume by periodically filling and emptying four rigid measuring chambers. It assumes the amount of biogas produced by the number of refills and emptying which causes the counting wheel to rotate as the biogas passes through it. The pressure in the flow meter was measured using a manometer. Biogas composition was analysed before the biogas meter and after the scrubber using a handle-held biogas analyser. The biogas analyser used online natural diffusion, which consisted of a 2-in-1 combined infrared sensor to measure CH_4 and CO_2 and an electrochemical sensor for H_2S. The biogas analyser could measure methane and carbon dioxide, each between 0 – 100 Vol% and between 0 to 1000 ppm for hydrogen sulphide.

3.3.8 Biogas scrubber

Biogas leaving the flow meter went through a scrubbing stage to remove impurities such as H_2S, CO_2 and H_2O. H_2S and H_2O are corrosive to metal and harmful to humans (Latosov, Loorits, Maaten, Volkova & Soosaar 2017). The scrubber reactor was made from a 250 ml dreshel glass-washing bottle with a sintered glass end. The scrubber was made from tempered glass that was chemical-resistant to strong bases and allowed for the monitoring of precipitate formation during the chemical reaction. The sintered glass end of the dip tube disperses the gas into bubbles for a more efficient distribution of the gas for enhanced liquid-to-gas contact as depicted in Figure 3.5 (DWK 2018). The dreshel bottle allowed the biogas to bubble through and react with a prepared caustic solution on entry.

Biogas entered the reactor through an 8 mm pipe that was submerged into the liquid. As a result of pressure build-up in the biogas, it is forced to penetrate the liquid surface and exit it at the point of low pressure. Furthermore, the scrubber was kept in a shaded area to maintain a low temperature (below 25 ^{o}C) for dehydration/ reflux of water vapour in biogas (Steyn 2017).

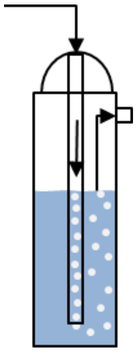


Figure 3.5: Schematic representation of the biogas scrubber reactor

3.3.9 PVC Tarpaulin biogas holder

The VUT-1000C plant was expected to produce at least 1000 L of biogas per day; thus, an adequate biogas storage facility was put in place. This reservoir allowed electricity generation testworks of the plants daily biogas yield to be undertaken with a steady and controlled biogas flow. A PVC tarpaulin biogas holder was used and was welded into a 1000 L bag. PVC tarpaulin is commonly used in making a flexible low-pressure biogas holder either externally as a balloon or by building it onto a complete mix digester tank as its roof. PVC tarpaulin was excellent for this application due to its resistant properties to abrasion and corrosion or contamination by acids. Furthermore, due to the chlorine in the PVC material, it is fire resistant (Envorinex 2017). Lastly, the material is gastight. In this study, the biogas holder was used as an external balloon which can be applied with weights to increase biogas pressure in the absence of a biogas compressor as depicted in Figure 3.7a. STH-1000A stored biogas internally, within the reactor vessel above the digestate as depicted in Figure 3.6. The digestate had the capacity to store up to 400 L of biogas. Similarly, in the absence of a biogas compressor or floating box a weight can applied to the digester in Figure 3.7a.

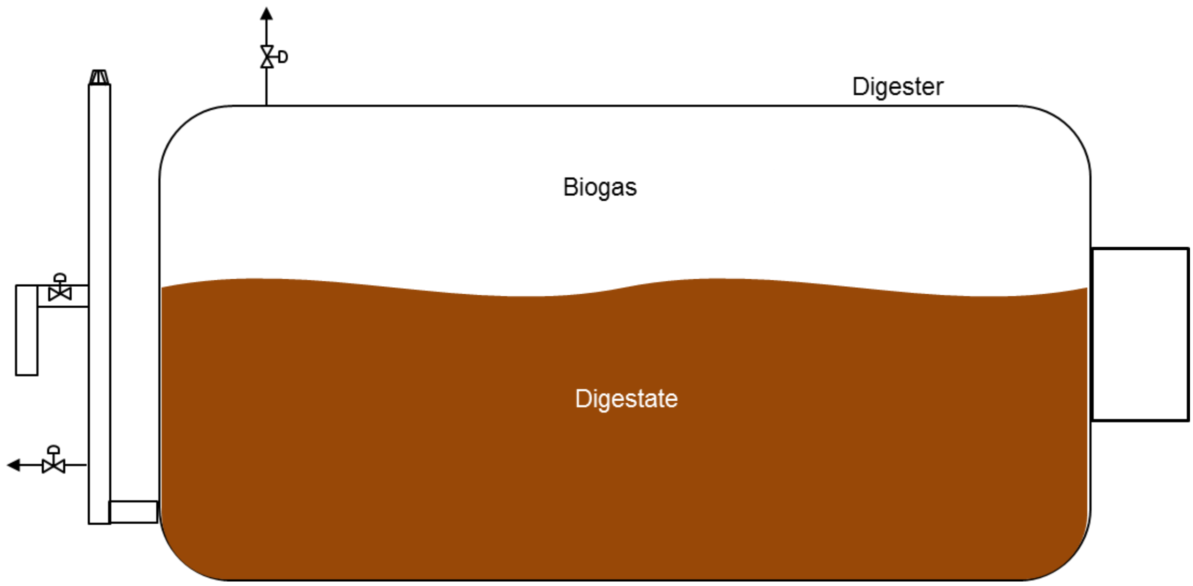


Figure 3.6: STH-1000A schematic representation of biogas and digestate sections in reactor

3.3.10 Floating box and drum biogas holders

Another form of biogas storage available for use in this study was a floating box. The floating box consisted of two identical boxes, each open at one end and closed on the other. The two boxes differed slightly in width to allow for insertion. Together they formed a single rectangular box closed on both ends. The smaller box was inverted and inserted into the bigger box and had fittings for biogas release attached on the closed end. The big box carried 200 L of sealing water and the small box carried 200 L of biogas. The boxes were made with different materials because of different strength requirements. The bottom box required more strength to carry the sealing water, therefore, strong rigid material, such as 5 mm glass was used. The top box did not require strength but it had to be lightweight to maintain low pressures in the digester, therefore, a 3 mm plexiglas was suitable for this application. The floating box provided 100 pa of pressure.

The floating box moved up and down to accommodate for changes in biogas volume. When biogas was produced, it floated up and when biogas was released, it sunk. The floating box acted as a biogas blower and pressure relief system. Upon excess biogas production, the biogas bubbled through the bottom rim of the box. Moreover, when releasing biogas, the weight of the top floating drum pressurised biogas such that it flowed to downstream processes.

The design of this conceptual floating box was unique,compared to conventional designs of floating drums. Conventional floating drums required additional support systems for the floating drum due to the lapsing that occurs when the top drum was completely lifted. However, in this design, the two vessels supported themselves by default due to the small spacing in between them and the four-cornered shape used, as depicted in Figure 3.7b.

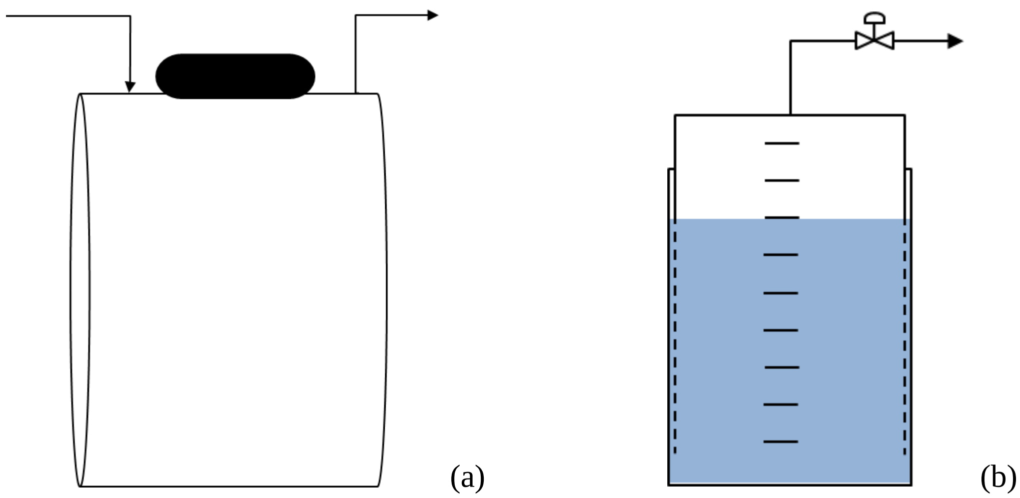


Figure 3.7: Schematic representation of (a) biogas holder and (b) floating box

3.3.11 Biogas generator

A small sized generator was used in this study. It consisted of a stationary magnetic field in which a rotating electromagnet spun to produce an electrical current. The internal combustion engine drove the rotating shaft that turned the electromagnet. The combustion engine was air-cooled and was a four-stroke single-cylinder engine. The generator had a maximum power output of 1.8 kW and 1.5 kW rated power output. Appliances could be plugged to a 12 V 8.3 A DC connection, DC and AC 220 V single-phase two-holed sockets. Inlet biogas pressure was required to be between 2 - 6 kPa. The generator consumed 0.65 m^3 of biogas per hour, as outlined in Table 3.2. The generator featured an electric starter connected to a 12V 7.4 Ah battery.

Table 3.2: Biogas generator properties

Item description	Value
Type	Biogas Generator
Rated power	1500 W
Maximum Power	1800 W
Frequency	50 Hz
DC Output	12V 8.3A
Generator Type	Bruss, copper, generator, single cylinder, 4-stroke, air-cooled
Engine Type	168FG
Starting Method	Electric starting
Ignition System	T.C.I.
Engine Oil Capacity	0.6 L
Gas Consumption Rate	0.65 m3/h
Gas Pressure	2 - 6 kPa
Biogas composition	>50% $CH_{4,}$ $_{<}$40%$CO_{2,}$ $_{<5}$ ppm H_2S
Continued Working Time	Cool after continuous operation of 4 hours
Standard Equipment	European two-holed socket with cover/ American three-holed socket
	1 AC, 220V single phase
	2 DC 220V single phase
Dimensions	610x440x455 mm
Weight	41 kg

3.4 Commissioning of biogas pilot plant (VUT-1000C)

Before test work commenced, commissioning of the system with tap water was performed to evaluate plant heating effectiveness along with fittings and connections integrity. After filling the reactor with water, it was checked for leakages. The water was then heated from ambient to mesophilic temperature. The duration of heating was recorded along with sudden temperature fluctuations. The boiler was turned on and set to 60 ^{o}C and the temperature controller was turned on and set to 38 ^{o}C. Upon inputting the set points, the boiler heated up the digester.

3.5 Biodigester start-up and organic loading optimisation

Anaerobic digestion was initiated by inoculating the digester with 200 kg of CD batch-wise. The CD had a wet-fine consistency and black in appearance with a brown overtone, it also contained soil and large particles.It was screened for soil and large particles greater than 3 mm that could be hazardous to the grinder pump. The screened CD was then fed to the digester, which contained 600 L of preheated tap water to obtain a working volume of 800 L in the 1000 L digester. Forster-Carneiro, Perez & Romero (2008) reported that up to 30% of the digester working volume should be filled with inoculum. At the beginning of the startup and after 24 hours of stabilisation, biogas volume, biogas composition, digestate pH and temperature were monitored daily. Inoculation was allowed to proceed until biogas cumulative difference was less than 1%. At the end of the inoculation, the OLR was varied. The optimal OLR was determined by feeding the digester batch-wise with different organic loads of 1, 2, 3, 5 and 7 kgVS/m^3. FW was collected, blended and stored in a shaded area in bulk batches of 60 - 100 L. The different loads were obtained by diluting FW with tap water. A load was added to the digester and allowed to digest until the biogas accumulative difference was less than 1%. At this point, a higher load was introduced. During the digestion at each OLR, several parameters were monitored.

3.6 Biodigesters operation at optimal OLR

After determining the optimal OLR of VUT-1000C, the digester was fed daily semi-continuously using the draw and fill method. STH-1000A was operated at the manufacturer's optimal OLR using the same feeding technique as VUT-1000C. For instance, on the first day of digestion at optimum OLR, after withdrawing 7 L of digestate, the reactor was fed with 7 L of FW containing 1.5 kgVS/m^3. To mimic practical digester operation, with daily semi-continuous feeding intervals, an organic load of 1.5 kgVS/m^3 was fed daily instead of 3 kgVS/m^3 every second day for VUT-1000C and 0.446 kgVS/m^3/day for STH-1000A. In practice, this came out to be 7 L of the food-water mixture at a ratio of 3:2 for VUT-1000C and 6 L of food-water ration of 1:1 for STH-1000C. Digestate pH, temperature and biogas production and composition were monitored in 24-hour intervals. Produced biogas was stored in a 1 000 L and 200 L biogas holder for VUT-1000C and STH-1000A, respectively.

3.7 Biogas conversion to electricity

With a full biogas holder, biogas was converted into electricity. A biogas compressor was connected between the biogas holder and generator to pressurise the biogas to 2 – 6 kPa. The generator engine was started using an electrical ignition starter, with the choke fully closed. The choke remained closed throughout the operation. Devices and gadgets with a total power consumption of 1500 W were connected to the generator. A wattmeter was connected between the generator and appliances to measure power output.

3.8 Chemical and physical analysis

Samples of the blended feed and digestate were removed and measured for total solids (TS) and volatile solids (VS) using the standard method of analysis. The substrate was dried at 105 ^{o}C to constant weight to determine TS and the dried substrate was ignited at 550 ^{o}C to determine VS (APHA 1998). Alkalinity in the digester was analysed by measuring digestate pH using a pH meter. The digester temperature was measured using a digital STC-1000 temperature controller connected to a thermocouple. Biogas composition was analysed with an online natural diffusion hand-held biogas analyser (as the gas chromatography on campus was out of commission). The infrared spectroscopy is a powerful tool for qualitative and quantitative gas analysis based on the interaction between infrared radiation and organic molecules (Köhler*et al.* 2017).

3.9 Experimental design

Upon the completion of digester design, construction and commissioning, in this experimental design, one factor was varied while the rest kept constant. Parameters kept constant were temperature, pH, mixing and solids concentrations while determining the effect of changing the organic loading rate on biogas production.

3.10 Conclusion

In this work, a ‘one factor at a time’ design factor has been applied with the main aim of evaluating the effect of organic loading rate on biogas production. The ambient and controlled biogas plants have been described in detail. The VUT-1000C was designed and commissioned successfully for this projects test works.

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CHAPTER 4: RESULTS AND DISCUSSION

4.1 VUT-1000C Biodigester commissioning

Tap water was used during the commissioning of VUT-1000C. The temperature profile obtained during the commissioning is represented in Figure 4.1. The temperature profile indicated a clear steady increase in digester temperature. It was observed that the boiler's temperature fluctuated with fluctuating daily ambient conditions. The initial temperature of the digester was 24.1 ^{o}C and reached 37.3 ^{o}C in 10 days. From day 9 to day 14, the digester temperature dropped to 32 ^{o}C, losing 5 ^{o}C of heat, which was due to cold, cloudy weather, as it was raining for five days. During rainy days, the boilers temperature decreases; as it was not receiving heat consequently, the heat was lost to the digester. The weather cleared from day 15 and the digester temperature reached 38 ^{o}C in 6 days. It can be observed that after day 30 the digester temperature remained stable, which is due to the heat capacity built up in the boiler being sufficient to maintain the digester temperature with minimal fluctuations.

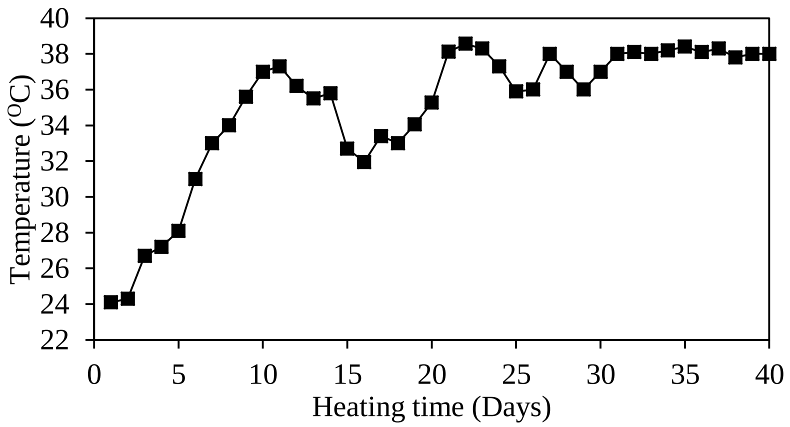


Figure 4.1: Temperature profile of VUT-1000C during commissioning

During the commissioning of the heat system, it was noted that the temperature controller was working as desired. Once the set point was reached, the pump turned off and the digester temperature exceeded the set point by a maximum of 0.8 ^{o}C only. However, during the night, the digester temperature dropped by 3 ^{o}C, which was due to insufficient insulation. The reactor top area required insulation. After adding more insulation to the roof of the digester and the digester, temperature remained at set point during the night.

Furthermore, mixing was critical in maintaining a homogenous temperature profile within the digester constantly; it provided heat circulation. To maintain a homogeneous temperature profile within the digester, a timer was installed to turn on the digestate-mixing pump for 15 minutes hourly.

4.2 Characterisation of inoculum and food waste

The biodegradability of a substance can be determined by its physical-chemical characteristics. The physical characteristics influence the performance of anaerobic digestion by affecting the methane yield and process stability (Zhang *et al*. 2007). The biodegradability of the food waste (FW) and inoculum were measured by determining the substances moisture content (MC), total solids (TS) and volatile solids (VS) percentage as listed in Table 4.1. A high amount of moisture in a substance makes it suitable for anaerobic digestion (Xu *et al*. 2018). In this study,FW was found to contain 85% of MC and the inoculum contained an average of 53%. The VS% contents in the substrate represent the biodegradable matter. The average VS contents obtained for FW and inoculum was 14 and 16%, similar to that obtained by Kuczman *et al*. (2018) who obtained 13% for FW and Dhamodharan *et al*. (2015) obtained 15.25% for inoculum.

Furthermore, the VS/TS ratio is an indicator for evaluating a substrates suitability for biogas production; substrates with higher VS/TS ratio contain higher organic matter and thus more suitable for biogas production (Wang, Hong, Lu, Li& Liu2017). In this study, VS/TS for FW was found to be 95%, an amount similar to that of Zhang *et al*. (2011) of 94%. These high values indicated that the FW was rich in biodegradable matter and thus excellent for biomethane potential. Substrates with VS/TS higher than 80% are considered as great candidates to be anaerobic digestion feedstock (Zhang *et al*. 2013; Illmer &Gstraunthaler 2009). The VS/TS ratio for the inoculum was 35%, which demonstrated that there was a small fraction of organic matter to be digested.Substances with values below 17.4 to 10% are considered inorganic (Kuczman *et al.* 2018).

The inoculum used for the startup of the prototype VUT-1000C biodigester had a pH value of 7.3, which is suitable for methanogenic bacteria. The pH of the inoculum contributed to the neutralisation of the FW pH, which was 4.

Table 4.1: Characteristics of CD and FW

Parameter	Cow dung	Food waste
MC (%)	53	85
TS (%)	47	15
VS (%)	16	14
VS/TS %	35	95
pH	7.3	4

4.3 VUT-1000C Biodigester startup

CD was pre-incubated as inoculum in the prototype biodigesters for a period of 55 days to create the suitable environment for FW digestion. The reason for the pre-incubation instead of feeding the inoculum and FW simultaneously was to obtain the methane yield of the FW only, independent of the inoculum (Dhamodharan *et al*. 2015). Inoculum plays a key role in the startup of a biodigester for the balancing of bacterial culture known as syntrophobacter and methanogens. This cultural balance aids syntrophic breakdown, which is thermodynamically feasible in anaerobic digestion (Pandey, Ndegwa, Soupir, Alldredge& Pitts2011).

During the first 14 days of inoculum incubation, no biogas production was observed. The liquid surface in the digester had a solid scum, which was caused by the lack of anaerobic conditions. On the 20^{th} day, bubbles started to form on the liquid surface, which, according to Parajuli (2011), indicated the start of biogas production; on day 22 and subsequently, the biogas meter recorded biogas production as given in Figure 4.2. The lack of biogas production during inoculation was due to an opening in the digester dome. The crack was identified and filled on day 20. From day 20 a maximum daily biogas production rate of 420 L was obtained, followed by a gradual decline in the daily biogas production. The cumulative biogas production curve was allowed to plateau to a point where the difference in daily biogas production was less than 1% before introducing FW (Elbeshbishy, Nakhla& Hafez2012). A total of 4015 L of biogas and 2056 L of methane gas were produced during this period.

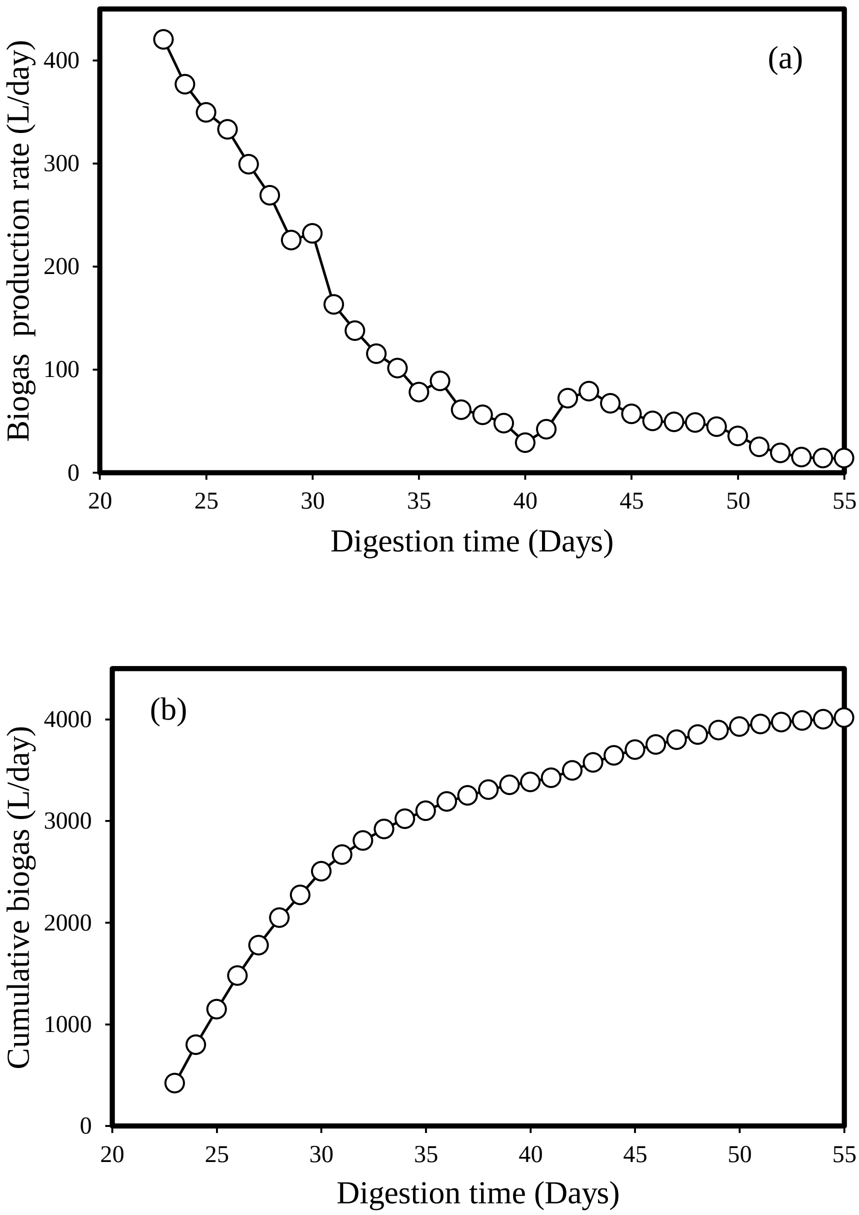


Figure 4.2: Daily (a) and cumulative (b) biogas production during inoculation of the biodigester.

4.3.1 Effect of temperature during VUT-1000C biodigester start-up

A temperature error was observed in the temperature profile of the digester as shown in Figure 4.3. From day 20 to 35, digester temperature readings ranged between 50 to 60 ℃. The high temperature observed was due to a faulty thermocouple in the digester. When the controller read temperatures higher than the set point of 37 ^{o}C, the hot water circulation pump was turned off, resulting in no heating in the digester. Consequently, the actual digester temperature decreased from 38 to 29.6 °C. Due to the decreased digester temperature, biogas production declined. The manual temperature digester readings are given from day 36 to 41 (Figure 4.3), the digester temperature decreased from 41 to 29.6 ℃ due to the lack of hot water circulation and insufficient insulation around the reactor. The thermocouple was replaced and insulation glass wool was placed on top of the reactor to add more insulation around the reactor. From day 41 to 55, there was an increase in daily biogas production due to the increase in digester temperature as a result of corrected temperature control (Figure 4.3). The digester temperature increased from 29.6 to 41 ℃.

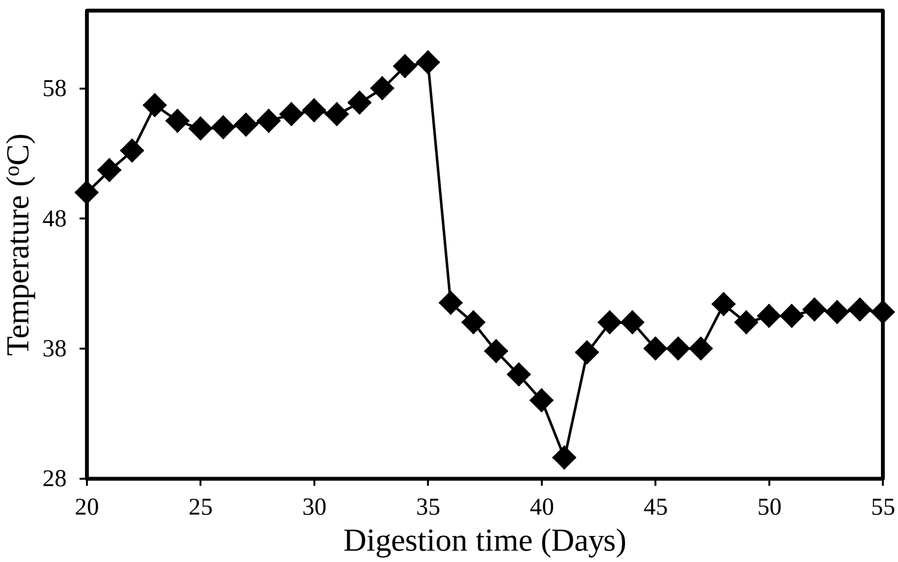


Figure 4.3: Temperature profile for the VUT-1000C biodigester during inoculation.

4.3.2 Biogas composition during VUT-1000C biodigester start up

Despite the fluctuations in digester temperature, methane composition as shown in Figure 4.4, remained relatively constant. The methane composition ranged between 42 and 59% and CO_2 between 18 and 25%, while H_2S ranged from 0 to 49 ppm. The fluctuations observed are due to a faulty flowmeter and does not have a significant effect on the data collection nor the performance of the digester. The flammable biogas contained an average of 54% CH_4 and 24% CO_2 and 17 ppm of H_2S. The unaccounted volume of gas by the biogas analyser could be ascribed to traces of different gases (H_2S, NH_3, H_2, N_2, O_2, CO). From these results, it can be confirmed that methanogenic conditions were successfully obtained during inoculation.

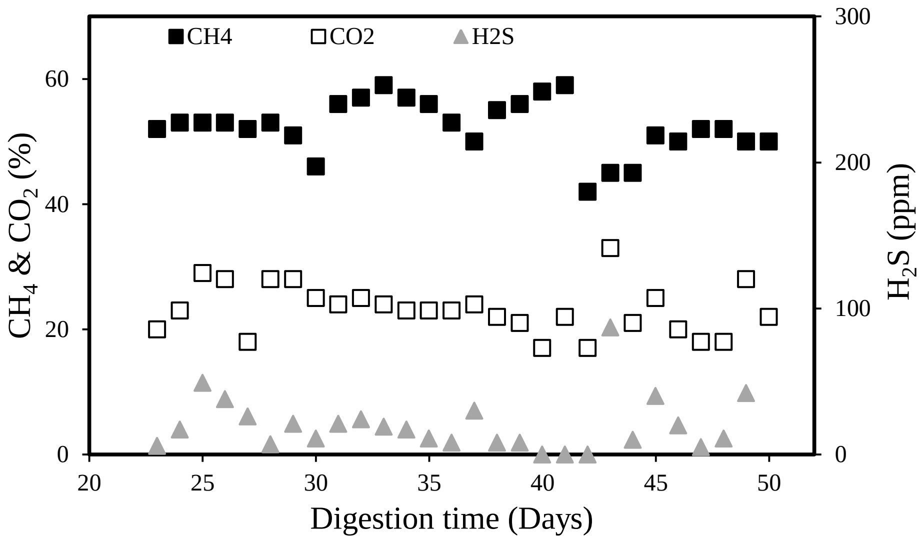


Figure 4.4: Biogas composition during VUT-1000C biodigester startup

4.3.3 pH trend during VUT-1000C biodigester startup

The pH remained stable throughout the inoculation period and within the methanogenicfavourable range as shown in Figure 4.5. The digestate pH level ranged between 7.2 and 7.5 over 55 days. The methanogenic bacteria require a pH between 6.8-8.2, according to Gunnerson and Stuckey (1986) and Thom (1994). The digester pH level was self-regulated, thus there was no buffer solution added to the reactor to adjust pH levels, which indicated an excellent digestate buffering capacity introduced in the biodigester.

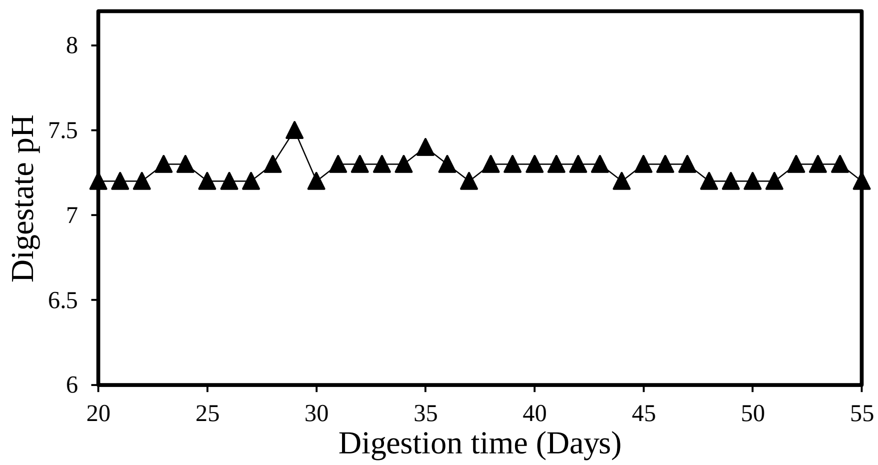


Figure 4.5: Anaerobic Digester pH during VUT-1000C biodigester start up

4.4 Effect of organic loading rate during VUT-1000C biodigester operation

The organic loading rate of FW into the biodigesters plays an important role in obtaining the highest bacterial activity. At the optimum organic loading rate, the highest amount of methane-rich biogas can be obtained along with other parameters favouring anaerobic digestion. Different organic loading rates were composted and the digester performance was studied.

4.4.1 Effect of organic loading rate on biogas production

After the startup period of 55 days, digestion of FW at different OLR was monitored by evaluating pH, biogas composition and biogas and methane yield. Biogas hourly production rate and cumulative productions for the first 40 hours of FW digestion were monitored. From Figure 4.6, biogas production occurred in a series of peaks, starting off with two main peaks - the second one being the highest. These peaks took place between hour 2 and 13, with the highest peak occurring between hour 8 and 13. This was an illustration of intense biogas production during the initial hours after digester feeding. A similar observation was made by Koch, Helmreich& Drewes (2015) who reported that the intense biogas production was an indication of the presence of readily degradable compounds. The highest biogas production rate peak was 131 L/hour for OLR 7. Liu, Wang, Anwar, Ma, Liu& Zhang (2017) obtained the highest peak of 0.8 L/day at OLR 7.5 and 10 kgVS/m^3 and El-Mashad and Zhang (2010) obtained 59 L/LkgVS/day at 2 kgVS/m^3 within the first day of digestion.

Cumulative biogas production increased with an increase in loading, with OLR of 1, 2, 3, 5 and 7 kgVS/m^3 producing 544, 931, 1746, 2334 and 2796 L of biogas, respectively, as depicted in

Figure 4.6. The hourly production rate dropped significantly within 40 hours for OLR 1, 2 and 3 kgVS/m^3,whereas OLR 5 and 7 continued at significant production rates averaging 20 and 50 L/hour, respectively. Approximately 80% of biogas was obtained within 40 hours of digestion time for OLR 1, 2 and 3; whereas, up to 50% was obtained for OLR 5 and 7 within the same period. This indicated that continued daily organic loading at high rates might result in system overload due to organic compounds accumulation and thus hindering microbial activity. Methane production and accumulation are critical in evaluating methanogenesis during digestion.

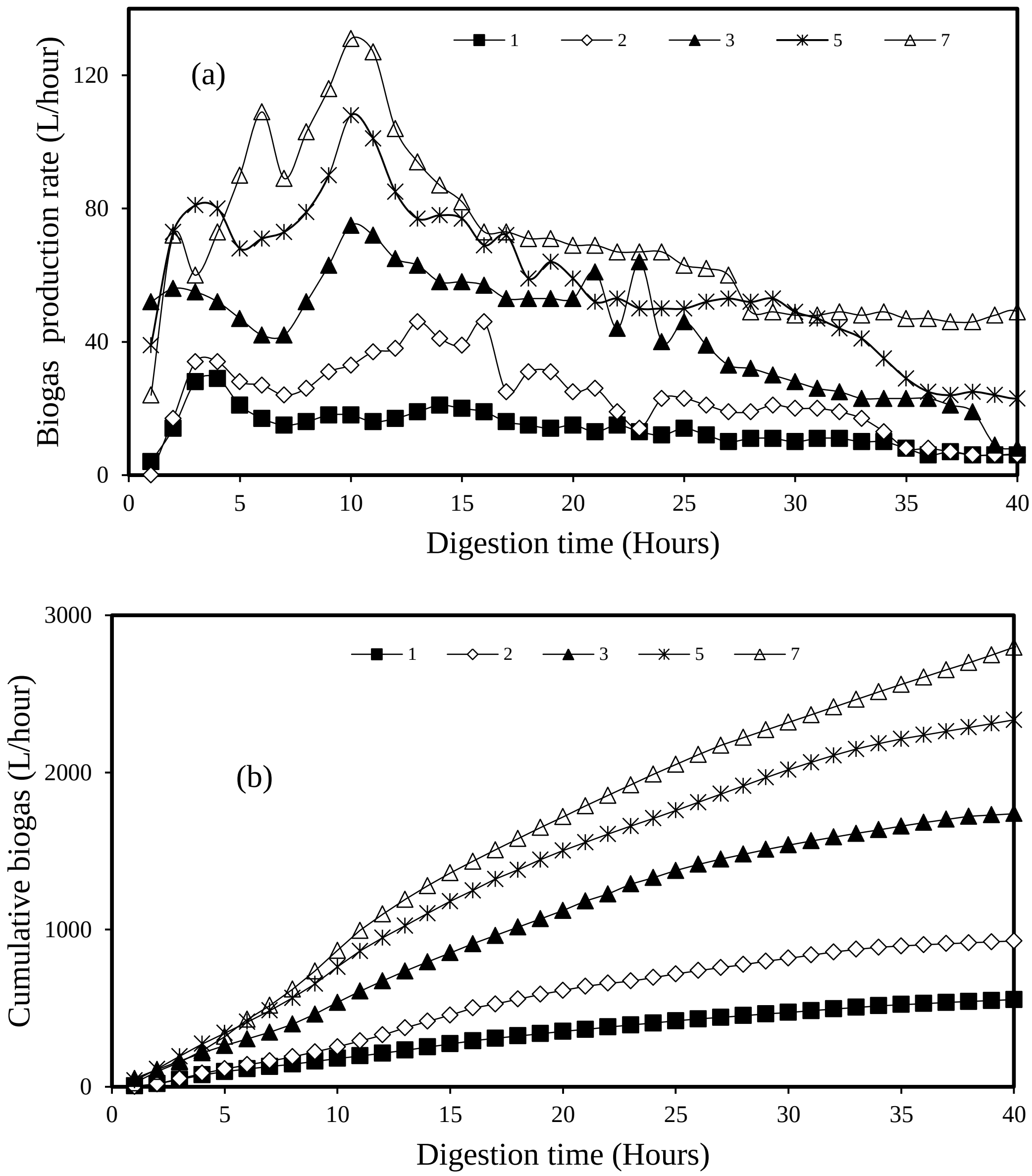
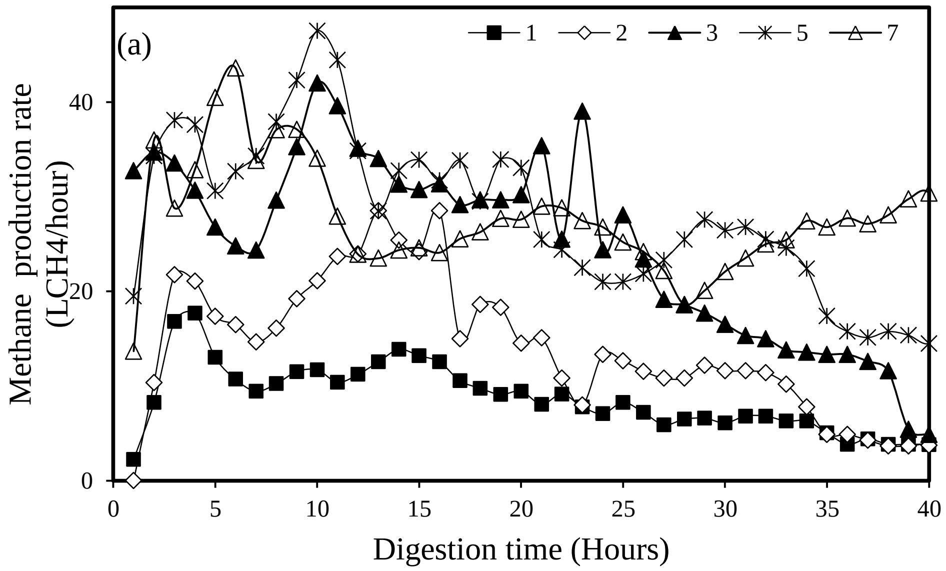


Figure 4.6: (a) Biogas production hourly rate and (b) cumulative biogas production during anaerobic digestion of food waste at different organic loadings

4.4.2 Effect of organic loading rate on methane production

Similar to the biogas production profile shown in

Figure 4.6, the methane production profile comprised of a series of peaks as given in Figure 4.7. Koch *et al*. (2015) observed a similar trend in their first 100 hours of co-digestion of FW with municipal wastewater. There was an increase in methane production with increase in organic load to a limit, which was OLR 3 kgVS/m^3. OLR 5 and 7 kgVS/m^3 showed no clear trend in methane production as shown in Figure 4.7a. The lack of a clear trend indicated instability of the anaerobic digester at high OLR. Figure 4.7b shows that OLR 3, 5 and 7 produced almost similar cumulative methane within the first 40 hours after digester feeding. These results show methane inhibition beyond OLR 3, which confirms digester overload, thereby hindering microbial activity (Liu *et al*. 2017).



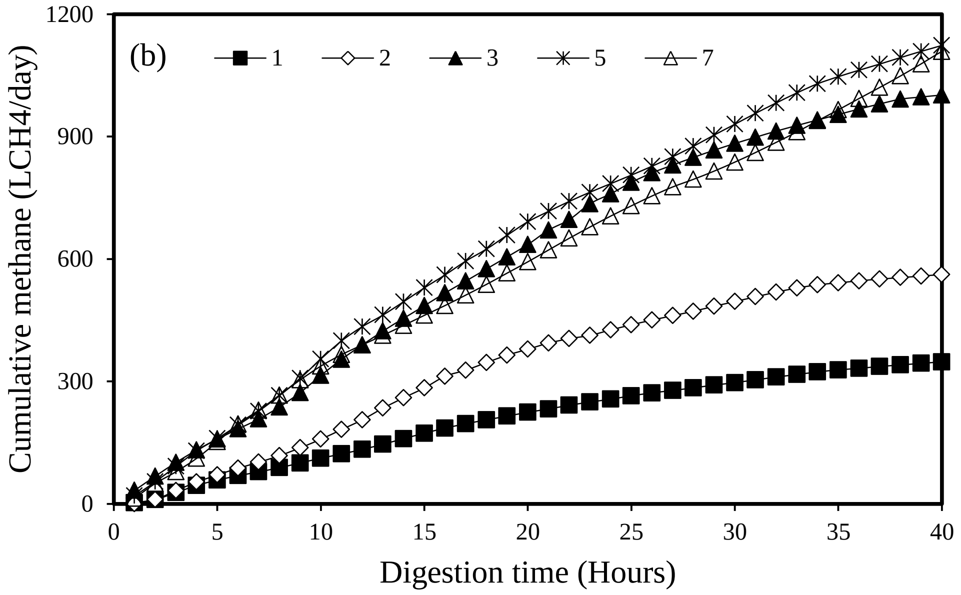


Figure 4.7: (a) Hourly rate and (b) cumulative methane production during anaerobic digestion of food waste at different organic loadings.

Methane production for the OLR of 1, 2 and 3 $kgVS/m^3$ was highest at 18, 29, 42 L/hour on hour 4, 16 and 10, respectively, which was reduced to 5 L/hour by day 39. OLR 5 and 7 $kgVS/m^3$ had the highest methane production rate of 47.5 and 43.5 L/hour by day 10 and 6, respectively and by day 40, the methane production was still significant - exceeding 15 L/hour. Furthermore, after day 28, OLR 7 $kgVS/m^3$ methane production increased from 18.6 to 30.4 L/hour by day 40. This trend indicated the reduction in initial overload leading to enhanced microbial activity and therefore improved methane production. Koch *et al*. (2015) obtained the highest peak of 13.7 $LCH_4/kgVS$/hour within the first 10 hours of digestion.

4.4.3 Effect of organic loading rate on biogas and methane yields

The specific biogas and methane yield of FW after 40 hours at the various organic loads are represented in Figure 4.8. The graph shows a clear decrease in biogas and methane yield beyond OLR 3. Organic loads 1 and 3 $kgVS/m^3$ obtained the highest biogas and methane yields of 544 and 582 $L/kgVS/m^3$ and 348 and 332 $LCH^4/kgVS/m^3$, respectively. OLR 7 obtained the lowest specific biogas and methane yield of 399 $L/kgVS/m^3$ and 158 $LCH^4/kgVS/m^3$, respectively. OLR 3 gave the highest conversion of biogas from FW and thus was chosen to be the optimal organic load as per specific biogas and methane yield and the cumulative biogas production. OLR 3 produced three times more biogas and methane than OLR 1 in the same period, thus making it desirable. Babaee and Shayegan (2011) obtained the optimal organic load to be 1.4 $kgVS/m^3$/day which yielded 250 LCH_4/kg VS_{added}. El-Mashad and Zhang (2010) obtained 657 L/kgVS from FW after 30 days of digestion,79.1% of which was produced after 20 days of digestion. After 20 days of digestion, the methane yield accounted for 72.5% of 353 L/kgVS obtained after 30 days (El-Mashad and Zhanga 2010).

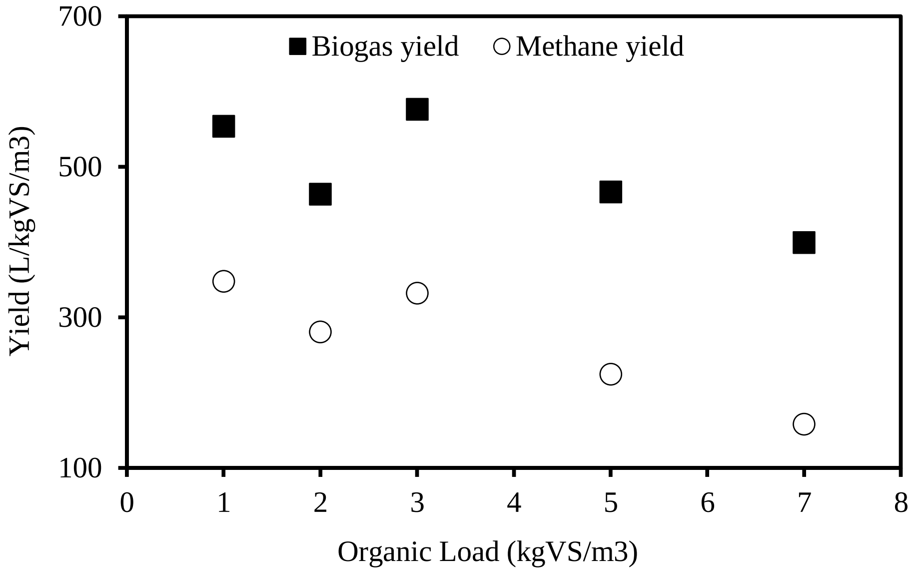


Figure 4.8: Specific biogas and methane yields of food waste at different organic loadings

4.4.4 Effect of organic loading rate on biogas composition

The composition of biogas produced at the different OLRs shows the methanogenic bacteria performance as shown in Figure 4.9. It was observed that increase in organic load resulted in the decrease in methane content and increase in carbon dioxide content at the early stages of digestion. Hydrogen sulphide content showed no significant response to organic load increase. The highest H_2S average content was 39 ppm. According to Pipatmanomai *et al.* (2009), H_2S content below 50 ppm is below toxicity levels and thus safe to be used in combustion electricity generators and biogas stoves.

At high OLR, methane content dropped and carbon dioxide content increased as shown in Figure 4.9a and b. The biogas quality for OLR 5 and 7 improved after hour 32 where methane and carbon dioxide contents were within the usable range for energy conversion. Furthermore, this is characteristic of the primary stages of AD, hydrolysis, acidogenesis and acetogenesis, producing CO_2. These stages have a higher growth rate than the methanogenesis stage (Chen *et al.* 2016). Thus, it is critical to maintain a loading rate that promotes methanogenic bacteria growth rate and prevent excessive acids and CO_2 build up that could inhibit the hydrogenetrophic methanogens (Chen *et al.* 2016).

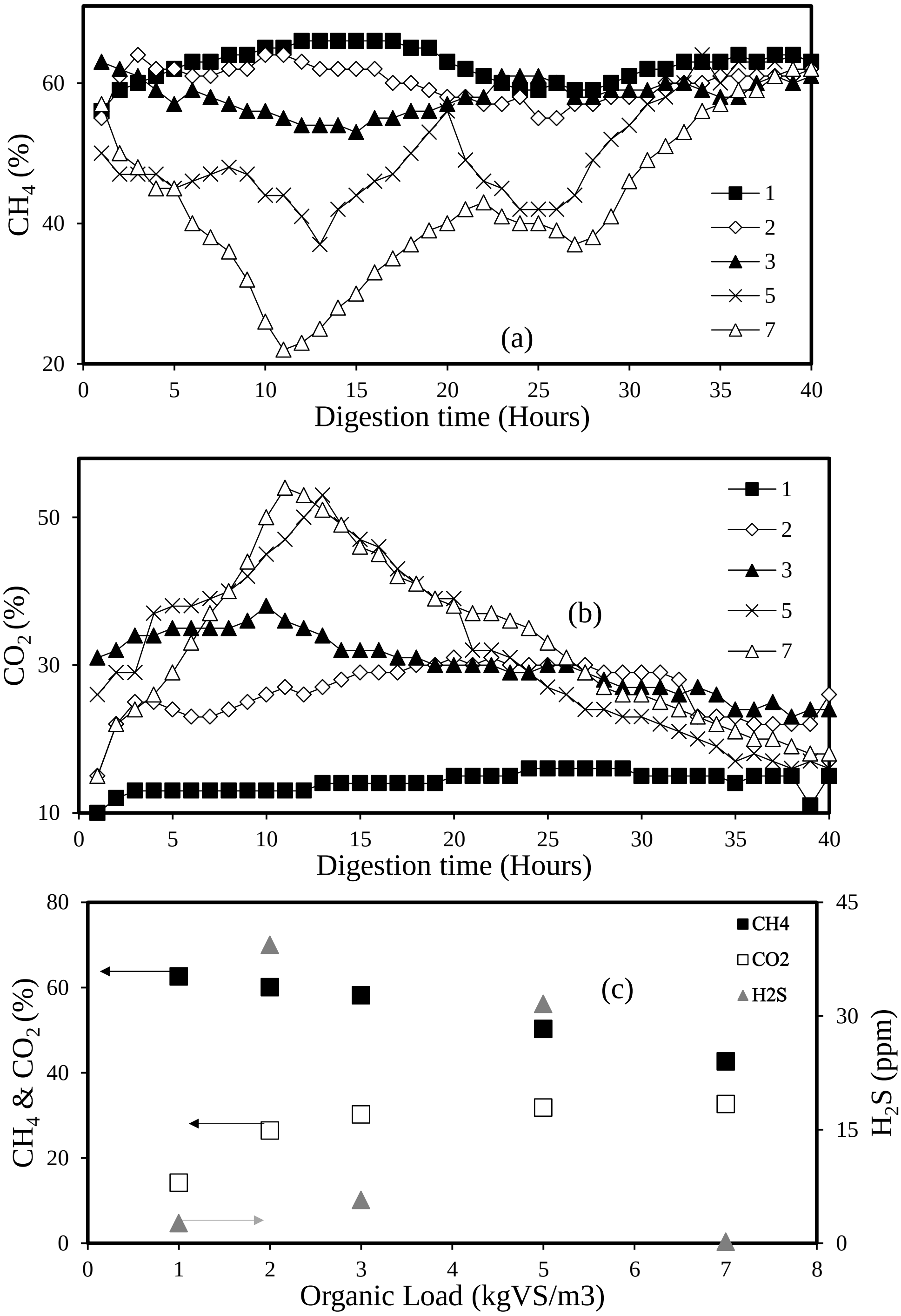


Figure 4.9: Hourly (a) methane and (b) carbon dioxide contents of biogas produced and (c) overall composition of cumulative biogas produced during anaerobic digestion of food waste at different organic loading rates.

After hour 13, there was a gradual decrease in carbon dioxide production as it was converted into methane. Consequently, methane content increased gradually after hour 13. OLR of 2 and 3 $kgVS/m^3$ followed a similar trend as did OLR 5 and 7 $kgVS/m^3$; biogas composition for the OLR of 2 and 3 $kgVS/m^3$ remained within favourable range throughout the digestion period, whereas for OLR 5 and 7 $kgVS/m^3$, the composition was compromised. The results for OLR of 1 $kgVS/m^3$ showed the most stable methane and carbon dioxide content throughout the digestion period. Methane content for OLR of 1, 2 and 3 $kgVS/m^3$ ranged between 53 and 66%, whereas OLR of 5 and 7 $kgVS/m^3$ ranged between 20 and 60%. The carbon dioxide content for OLR of 1, 2 and 3 $kgVS/m^3$ ranged between 10 and 42% and 15 and 64% for OLR of 5 and 7 $kgVS/m^3$.

The average composition of biogas at different organic loads for FW in

Figure 4.9c showed that increase in organic load resulted in the decrease of methane content and an increase in carbon dioxide composition. Higher organic loads resulted in a poor-quality biogas, which cannot be used as a fuel. The average methane and carbon dioxide contents for OLR of 1, 2, 3, 5 and 7 $kgVS/m^3$were 63, 60, 58, 50 and 43% and 14, 26, 30, 32 and 33%, respectively.

4.5 Kinetic parameters of anaerobic digestion

At steady-state, it can be assumed that the lag and exponential phases of methane production follow a first-order rate given by a linear regression model as:

$$\boldsymbol{B_t = B_p(1 - e^{k_1 t})} \qquad \textbf{(4.1)}$$

where k_1 is the first order biogas production rate constant (h^{-1}) and e is equal to 2.7183. The average hourly data for biogas accumulation production during steady-state was used for the linear plot shown in Figure 4.10. Based on the R^2 values, the model best described the optimum OLR of 3 $kgVS/m^3$ and corresponds with experimental data.

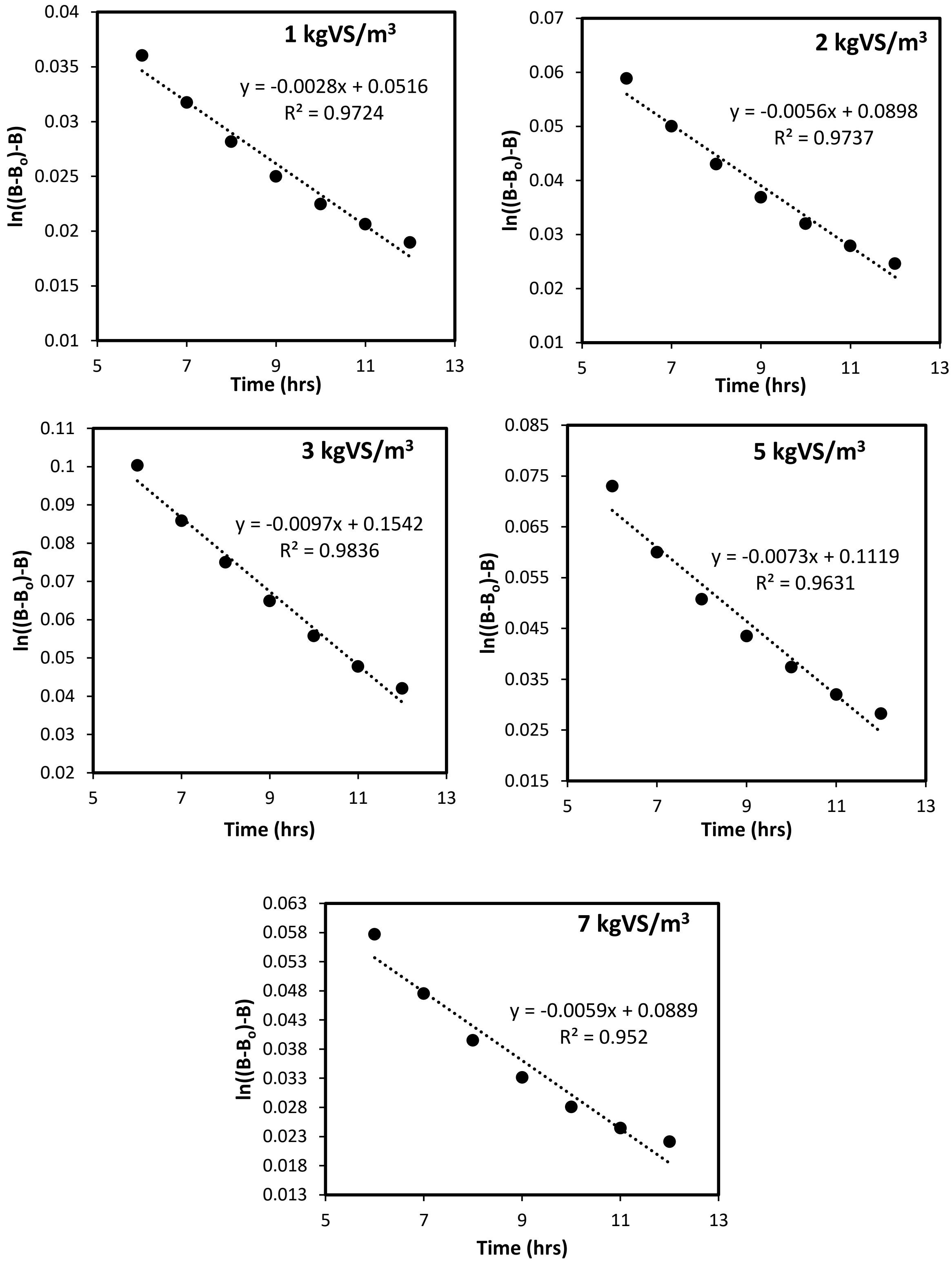


Figure 4.10: First order biogas production kinetics at 1, 2, 3, 5, and 7 kgVS/m^3

4.6 Comparison of semi-continuous operation of VUT-1000C and STH-1000A biodigesters at optimum conditions

The biodigesters were both operated at their optimal organic loading rates of 3 and 0.446 kgVS/m^3 for VUT-1000C and STH-1000A, respectively, for 35 days. This was done to monitor the daily operation of the biogas pilot plants and to determine their daily biogas production at optimum conditions.

4.6.1 Biogas and methane production during biodigesters operation at optimum conditions

Biogas and methane daily production daily rate for VUT-1000C increased gradually over the digestion period, which was due to the presence of residual substrate from previous feeds, which increases with additional feed (see Figure 4.11). The trend of gradual increase in daily biogas production at a constant organic loading rate was observed in Mu, Zhang, Zhu, Ma& Li (2018), Nagao *et al*. (2012) and Otieno (2020). A gradual increase from 341 L/day on day 1 to 1174 L/day on day 29 was observed. After day 29, the biogas produced remained constant at around 1200 L/day this indicated the achievement of steady state. On the first day, 341 L of biogas and 187 L of methane was produced and increased daily to a maximum average of 1319 and 791 L/day, respectively, on day 34. Furthermore, the graph consists of a series of peaks occurring on days 4, 12, 26 and 34; the reduction in biogas production post peak was due to the fresh FW introduced to the digester after the prepared bulk batch had been depleted. This was because feeding fermented food makes volatile fatty acids readily available to the microorganism in the digester; hence, fermented FW is more favourable than fresh FW as it improves biogas production (Baldi, Pecorini& Iannelli 2019).

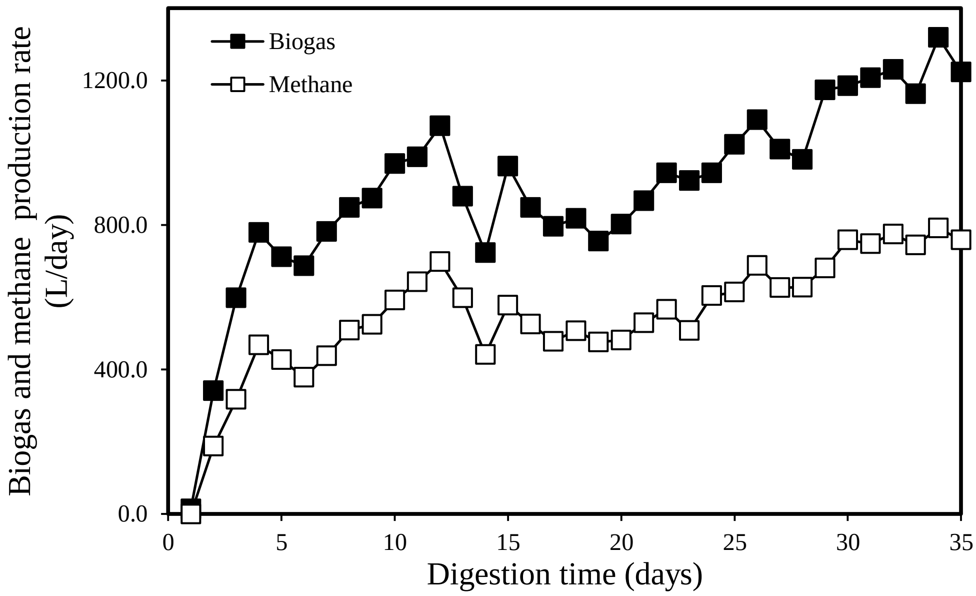


Figure 4.11: Daily biogas and methane production of food waste at 1.5 kgVS/m^3/day using bioreactor VUT-1000C

During the operation of STH-1000C, the biogas and methane production similarly increased gradually with time due to the build-up of residual substrate and growth of bacterial population. Biogas production increased from 37 L/day on day 2 to 150 L/day on day 27 (Figure 4.12). The digesters steady state was obtained on day 27 where biogas production remained around 150 L/day. On day two, 37 and 21 L of biogas and methane, respectively, were produced and on day 31, a maximum of 164 L of biogas and 110 L of methane was produced. The ever-changing ambient temperature did not cause the digestion process to be unstable; this was attributed to the insulative greenhouse structure covering the digester.

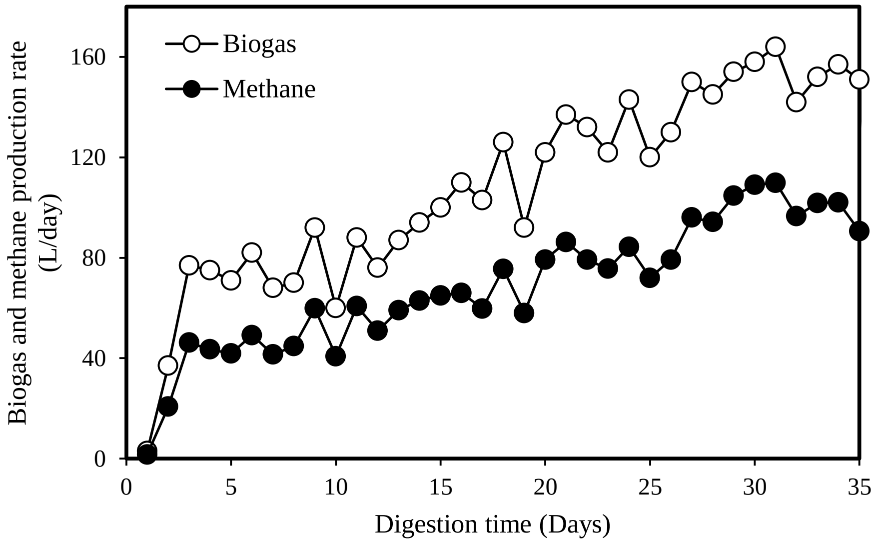


Figure 4.12: Daily biogas and methane production of food waste at 0.446 kgVS/m^3/day using bioreactor STH-1000A

On average, VUT-1000C produced 901 L/day of biogas and 551 L/day of methane over the 35 days' period while STH-1000A produced 108 L/day of biogas and 69 L/day of methane. This significant different in terms of biogas and methane production was due to the difference in digester design. First, the STH-1000A design operated at ambient temperature and biogas production thrives in elevated temperatures. Secondly, the digester did not allow for the maximum use of the reactor volume; it only allowed for a working volume half its reactor volume, instead of 80% as did VUT-1000C. These constraints in turn reduced the digesters optimal organic loading rate to a sixth of that of VUT-1000C, ultimately yielding very low biogas production.

4.6.2 Biogas composition and digester pH levels during optimum operation

For the VUT-1000C, biogas showed to be rich in methane content throughout the digestion period at optimum conditions with an average of 60% and a low concentration of CO_2 was obtained at an average of 29%and 94 ppm for H_2S. The highest methane concentration obtained was 68% on day 13 and the lowest carbon dioxide was 24% and 44 ppm for H_2S as shown in Figure 4.13. The graph shows that digestion conditions were stable and favourable for methanogensis. This can further be seen in the digestate pH levels in Figure 4.14. The pH was stable and ranged between 7.3 and 7.8 with no adjustment required. This was an indication of a high buffering capacity, attributed to inoculum and optimum OLR.

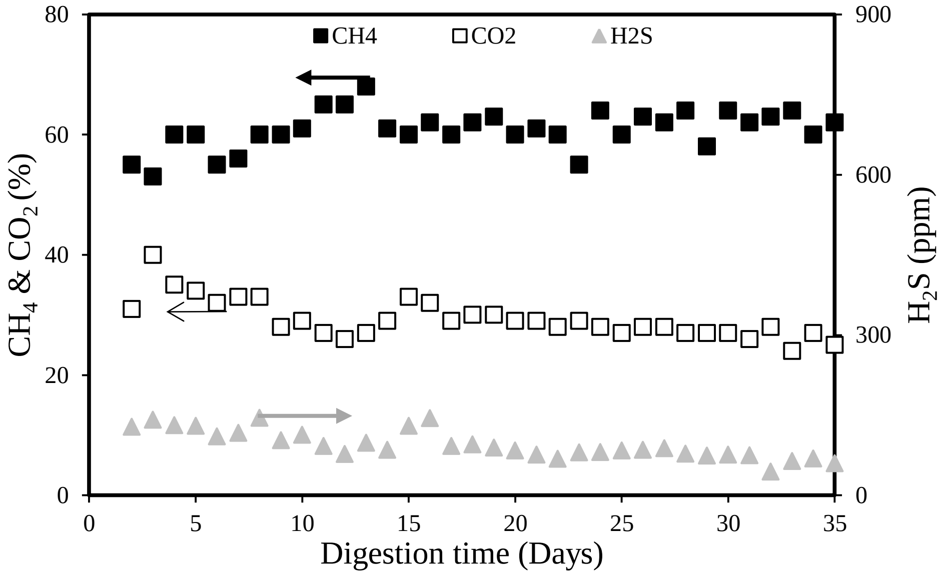


Figure 4.13: Daily biogas composition during anaerobic digestion of food waste at 1.5 kgVS/m^3/day OLR

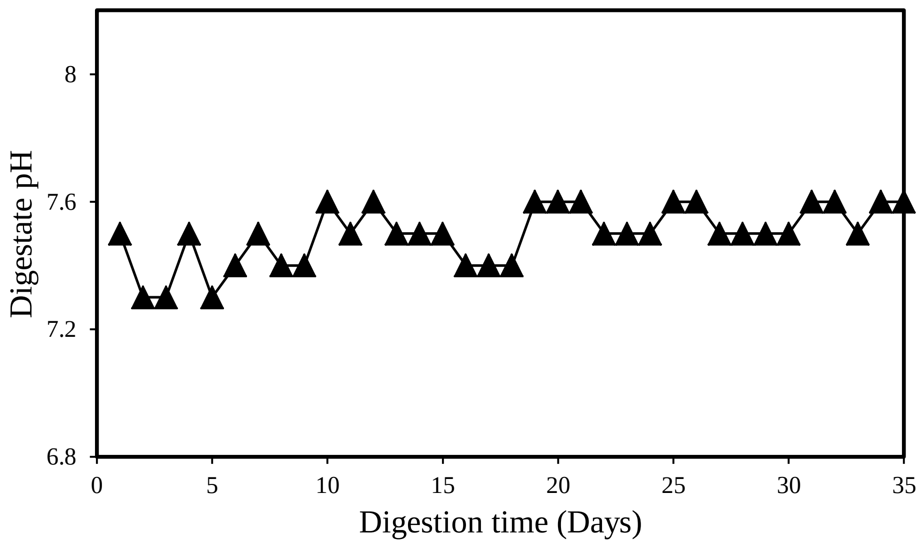


Figure 4.14: Digestate pH during anaerobic digestion of food waste at 1.5 kgVS/m^3/day OLR.

Similar to VUT-1000C, STH-1000A biogas was rich in methane content throughout the digestion period. Methane content ranged from 54 to 69%, 21 to 36% for carbon dioxide and

2 to 30 ppm for hydrogen sulphide. Biogas composition averaged 63 and 29.6% for methane and carbon dioxide, respectively and 7 ppm for hydrogen sulphide. Biogas produced from STH-1000A showed to contain less hydrogen sulphide than biogas from VUT-1000C by a difference of 87 ppm. The biogas composition trend produced in Figure 4.15 suggests that the methanogenic bacteria activity was favoured in VUT-1000C. Similarly, to VUT-1000C the pH level of the digestate in STH-1000A was stable as shown in Figure 4.16. Unlike VUT-1000C, pH was adjusted regularly to maintain these conditions. This may be attributed to the lack of sufficient seeding during digester startup.

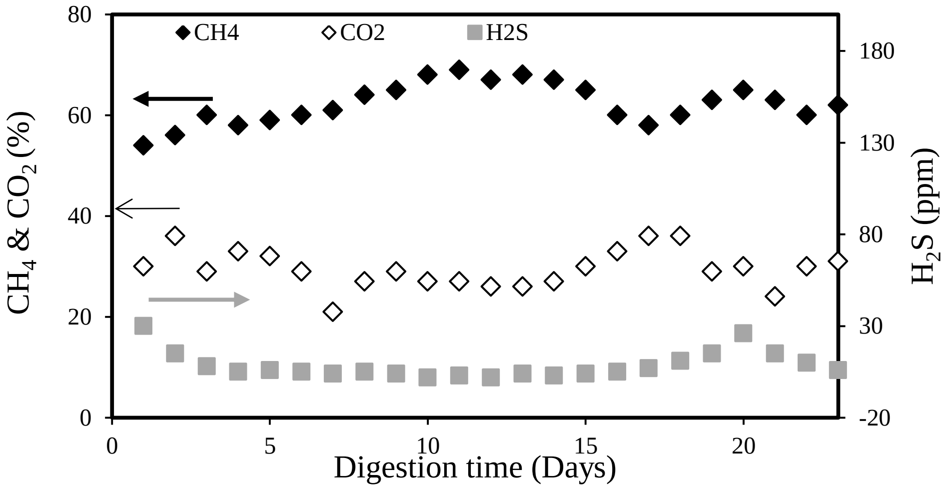


Figure 4.15: Daily biogas composition during anaerobic digestion of food waste STH-1000A

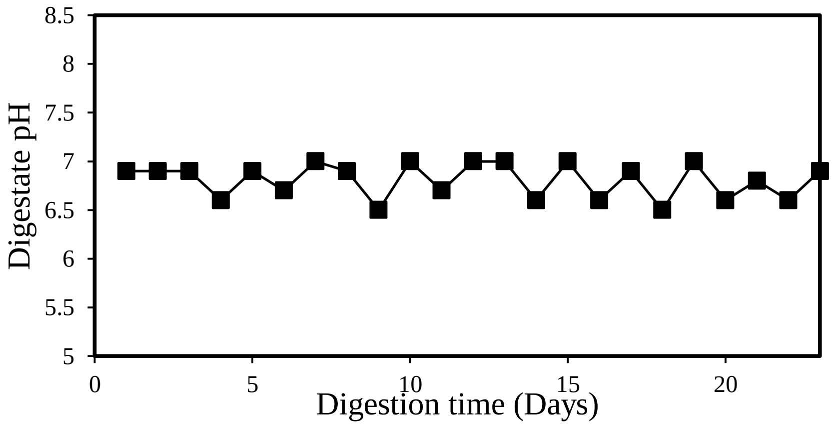


Figure 4.16: Digestate pH during anaerobic digestion of food waste for STH-1000A

4.6.3 Digester temperature profile during operation of biodigesters at optimum conditions

Digester temperature for VUT-1000C was maintained at 37 ^{o}C. Figure 4.17 outlines the temperature profile throughout the 35 days digestion period. The temperature ranged between 36.2 and 37.9^{o}C; maintained on solar energy only with no electricity backup. The fluctuation in temperature was due to the effect of ambient conditions changing. Long cloudy days lower the boiler water temperature and consequently the digester temperature dropped. Furthermore, during extremely hot days, thermosiphoning effect took place through the heating coil as the boiler water reached boiling point and consequently increased the digester temperature beyond set point. The change in temperature was not sudden in most cases and thus did not affect the stability in daily biogas production. The temperature deviated from the setpoint by a maximum of 1.2 ^{o}C. Solar heating of a biodigester proved to be very effective.

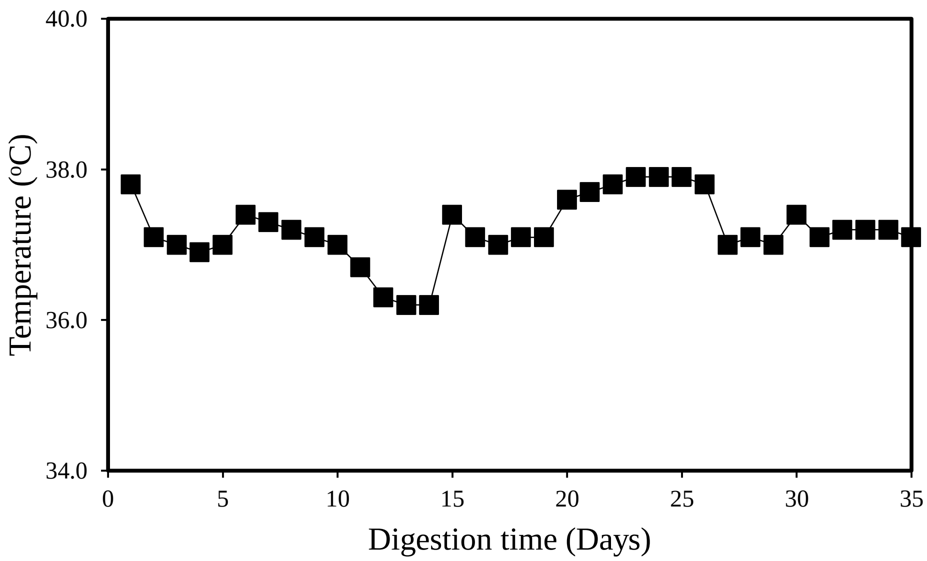


Figure 4.17: Digester temperature during food waste digestion

STH-1000A was operated at ambient temperature and the temperature of the environment and digester are shown in Figure 4.18. From the graph it can also be seen how the atmospheric temperature played a significant role in defining the digester temperature. Ambient temperature is typically unstable and fluctuating, as a result, there is no clear trend in the temperature profiles. The ambient temperature reached its lowest value of 22 ^{o}C on day 17 and highest of 42.9 ^{o}C on day 32 and on the same days the digester temperature was at its lowest of 24.1 ^{o}C and highest of 32.3 ^{o}C.

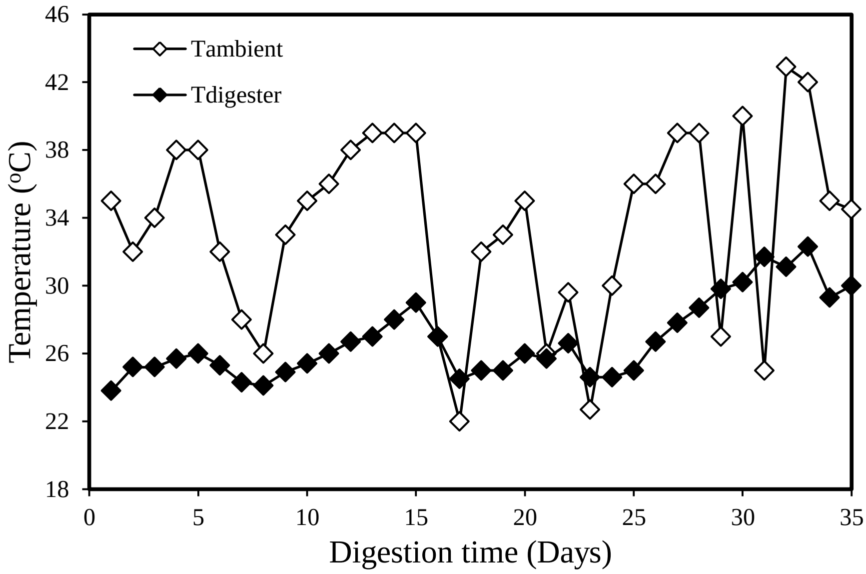


Figure 4.18: The effect of temperature change on biogas production at 0.446 kg VS added daily

4.7 Biogas conversion to electricity

An electricity biogas generator connected to a combustion biogas engine was used to generate electricity. A specific volume (1000 L) of biogas was used to perform the test work and a total of 2.3 kW was produced. The electrical output of the engine was 220 V, 50Hz and 1.8 kWh. A maximum of 1.8 kWh was generated with an overall conversion efficiency of 22%. The biogas consumption of the generator was 650 L/hour. On a national scale, this amount of electricity can light up to 300 6 W energy saver light bulbs for an hour.

Furthermore, in a rural setting where there is no electricity, this biogas pilot plant can provide electricity and allow the users to perform short-term energy-requiring tasks. By running the generator, a family would have a total of 2.3 kW for 1 hour 30 minutes (1.5 – 1.8 kWh) of electricity per day from 1000 L of biogas. From 2 kWh of electricity, the family can perform one of the following tasks or a balanced mixture of these tasks for their living requirements: microwave (700 W) 32 meals, toast (800 W) 48 slices of bread, vacuum clean (1400 W) 16 rooms, run three laundry loads (800 W), iron (150 W) full laundry, bake one cake (1300 W), blend food (400 W), charge devices (36 W) and drill (650 W) and grind (650 W) for 3 hours.

4.7.1 Energy balance for biogas production VUT-1000C

The energy balance considers the energy input to run the biogas pilot plant and compares this input with the energy output in terms of electricity. The temperature controllers used in this plant were operated continuously throughout the day and consumed a total of 8 W per hour, which are the lowest energy-consuming components of the plant. The two highest energy-consuming components of the plant were the food blender and digestate circulation pump. The food blender had the highest power rating; however, it was used only for 15 minutes a day, consuming 90 W. The digestate circulation pump was operated for 15 minutes per hour daily, thus it consumed 45 W. The hot water circulation pump ran continuously at start up for 2 days and then it would turn off when the set digester temperature was reached; then it ran for approximately 3 hours in the morning. On average, the hot water circulation pump used 1.3 W per hour daily.

When running the generator, the biogas blower was used to pressurise the biogas and it consumes 16 W per hour. In total, the energy input to run the entire biogas pilot plant per hour was 160 W. In comparison to a power output of 1800 Wh, the biogas plant requires 10% of its energy output. This is a positive result and proves the system to be a net energy producer.

Table 4.2: Power consumption of equipment used in biogas production and biogas use

Component	Power rating (W)	Power usage (W)
Digestate circulation pump	180	45
Hot water circulation pump	8	1
Solar geyser temperature controller	5	5
Hot water circulation controller	3	3
Food grinder	373	90
Biogas blower	16	16
Total	**585**	**160**

4.7.2 *Upscaling biogas energy potential*

From these results, South Africa's biogas energy potential can be estimated. South Africa produces 12 million tons of FW per annum (Oelofse & Nahman 2013). The biogas potential of this FW can be estimated using equations 1 and 2.

$$TVS = (FW * TS\%) * VS\% \qquad (1)$$

where TVS stands for total volatile solids in kgVS, FW is food waste in kg, TS is percent total solids and VS is percent volatile solids.

$$E_{biogas} = BY * TVS \qquad (2)$$

where E_{biogas} is biogas volume in L, BY is biogas yield in L/kgVS.

By operating a digester in the same conditions as reported in the present study, 12 million tons of FW per annum with VS and TS of 95 and 15%, respectively, would have a TVS of 1,938,000,000 kgVS. Annually, 1,703,502,000,000 L of biogas could be produced at a BY of 879 L/kgVS.

Biogas can be converted into electricity through small and large combustion engines. Larger engines have a combined heat and power capacity to provide heat to the anaerobic digester and other processes. Typically, small engines have a conversion efficiency of 22-25% and 35-40% for larger engines (Nielsen 2002 and Tafdrup 1995)

In the current study, an engine conversion efficiency of 25 and 40% is used to predict energy potential for small- and large-scale electricity generation, respectively. Equation 3 was used with the conversion efficiencies to determine the electricity potential from the biogas.

$$ebiogas[kWh] = Ebiogas[m^3] * 22\ [MJ/m^3] * 0.277778\ [kWh/MJ] * \eta \qquad (3)$$

where ebiogas represents the total electricity that can be generated from biogas in kWh, Ebiogas is the unconverted raw energy in the biogas in m^3, 22 MJ/ m^3 is biogas calorific value assuming 60% methane content, 0.277778 kWh/MJ is a unit conversion from MJ to kWh and η is the generator's overall conversion efficiency.

From 1 703 502 000 000 L of biogas 297 and 475 GWh of electricity at 25 and 40% conversion, respectively, can be generated from South Africa's current FW, which is enough to cover 1% of South Africa's household energy consumption of 47 trillion kWh, turning on 8 million 6 W lights per hour.

4.8 Commercial plants visited

The two main CHP plants visited were Johannesburg Waters Northern Water Treatment Works (JW NWTW) in Dieplsloot operated by WEC Projects and Tshwane 80 kWth Biogas Plant (TBP) in Bronkhortspruit.Both plants are based in Gauteng, South Africa.

The Diepsloot plant produces excessively high chemical oxygen demand (COD) sludge and utilises anaerobic digestion to reduce organic content while generating electricity and reducing their electricity bill. The plant produces 4.5 MW, covering approximately 56% of their power requirements and cutting back on their R100 million a year electricity bill for their wastewater treatment works. Their biogas plant consists of four concrete above-ground fixed-dome complete-mix anaerobic digesters with an external 300 m^3 metal floating drum applied as a biogas collector. The biogas plant further consists of a biogas scrubber and three generators each with an electrical output of 300 kW. The digester is heated using an external plate heat exchanger through which the slurry is pumped and circulated. The heating water is heated using two methods. First, the heating water receives heat from the electricity generators/biogas engine through the cooling system producing low-grade (±80 ^oC) heat and through the exhaust producing high-grade (±450 ^oC) heat. Secondly, heat is received from a boiler fuelled with diesel or biogas, depending on availability and plant operation stage. The digesters are fed semi-continuously at 5-hour intervals. pH adjustments are through lime supplementation. The biogas produced consists of 62% CH_4, 37% CO_2 and 0.04 O_2 and 452 ppm of H_2S after scrubbing. The biological scrubber utilises fertiliser and oxygen to reduce H_2S and activated carbon is used to reduce siloxanes. Produced digestate is donated as compost to the community. WEC Projects (Pty) Ltd. developed the JW NWWTW biogas CHP plant.

The TBP has a variety of feedstocks, namely, waste fruits and vegetables, chicken manure and sorghum. The plant produces electricity for approximately 15 chicken farms that have a household each and heat for the anaerobic digester. A total of 393 120 kWh is produced per year. The generator further produces sufficient heat to maintain mesophilic conditions within the digester. Produced liquid fertiliser is used in the farmers' food gardens. The biogas CHP plant consists of a single flexible top complete-mix anaerobic digester (the digester of the reactor was made from glass-fused-to-steel and then insulated with mineral wool that was protected with corrugated sheets), biogas scrubber and 80 kW generator. The flexible roof, when inflated, has a biogas capacity of 30 m^3. The digester is fitted with an internal heating coil forming a zig-zag pattern on one side of the digester. The circulated slurry enters such that it makes maximum contact with the coil; upon entry into the digester, the slurry is jetted toward the coil. In this plant, the heating principle from the generator is similar to that of JW NWWTW, with the exception of a boiler. The biogas produced is composed of 60% CH_4, 35% CO_2 and 5% trace gases. The biogas goes through a reflux device that removes sulphur and oxygen. In the reflux device, biogas bubbles through cold water and condenses free water particles. Upon exiting, the biogas is drawn through a stainless steel pipe, which remains cold and condenses any remaining water vapour. Botala Energy Solution (Pty) Ltd. designed and constructed the biogas CHP plant.

4.9 Conclusion

In this section, the results obtained from performing anaerobic digestion test works have been processed and discussed in detail with these major findings: Food waste (FW) proved to be a strong substrate for anaerobic digestion due to its high biodegradability. The optimal OLR for the FW was found to be 3kgVS/m^3(1.5 kgVS/m^3/day) for VUT-1000C and was supported by the modified Gompertz model with an R^2 value of 0.9836. The optimal OLR for STH-1000A was given to be 0.446 kgVS/m^3/day. From these optimal OLR, digestion stabilised at a biogas production of 1200 and 150 L/day for VUT-1000C and STH-1000A, respectively.

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CHAPTER 5: Conclusion and recommendations

5.1 Overall conclusions

Food waste (FW) is produced in large amounts worldwide daily at all levels of the food supply chain. This FW has a high organic load and moisture content. Due to these characteristics, if discarded, may cause a detrimental environmental impact with loss of renewable energy. The study aimed tocarry out anaerobic digestion (AD) of FW and determine the potential of generating electricity from the biogas produced. The study sought to design, construct and commission a complete-mix pilot biogas plant using locally sources material for this purpose. The digesters optimal organic loading rate (OLR) was determined to obtain the highest yield of biogas and methane. After determining the best OLR, the digester was semi-continuously operated to monitor the pilot plants' performance and obtain the stabilised biogas production rate. Thereafter, the biogas produced was converted into electricity. Energy balance analysis was then done to inform plant energy efficiency and energy potential in South Africa's (SAs) FW.

A complete-mix mesophilic pilot biogas plant was successfully designed, constructed and commissioned for biogas production and electricity generation. The construction of this pilot plant was to prove that the technology is within reach in SA, thus all parts used for the construction were sourced locally except for the generator engine. However, with a small modification to a locally purchased petrol generator carburettor, the generator can be sourced locally as well. The material and components of the plant used for the construction of the plant were of high quality and proved to be suitable for the reported study. The plant was easy to use and provided an odour-free environment. With this design, general skills are required for successful third party installation and operation. The digester temperature test work results showed that a 1 m^3 digester can be well heated to mesophilic temperatures using a 100 L solar heated geyser without electricity backup. The digester was heated from 24.1 ^oC to 37.3 ^oC in 10 days and was well maintained at that temperature with the aid of sufficient insulation. It was later found that when the solar geyser water was at temperatures between 80 and 100 ^oC, the digester could be heated from 24 to 37 ^oC in 2 days instead of 10 days.

Cow dung (CD) proved to be suitable for inoculation as it provided a favourable environment for digesting FW. For digesting highly acidic food substrate, CD introduced a high buffering capacity to the system. The complete incubation of inoculum took 55 days. pH levels remained stable throughout the study with no irreversible acidification typically experienced in the treatment of FW. During the OLR optimisation, it was observed that methane yield increased with increasing organic load to a limit beyond which the methane yield decreased. The optimal OLR for the FW was found to be 3 $kgVS/m^3$ (1.5 $kgVS/m^3/day$) for VUT-1000C and was supported by the modified Gompertz model with an R^2 value of 0.9836. The optimal OLR for STH-1000A was given to be 0.446 $kgVS/m^3/day$. During operations at optimal OLR, digestion stabilised at a biogas production of 1200 and 150 L/day for VUT-1000C and STH-1000A, respectively. At the end of 35 days operation, a total of 31 535 and 19282 L of biogas and methane, respectively, was produced from VUT-1000C and 3790 and 2409 L of biogas and methane for STH-1000A. These results show a significant improvement in biogas and methane production in the prototype design, VUT-1000C, over STH-1000A.

From 1000 L of biogas, 1.8 kWh of electricity was produced, which is equivalent to the amount of energy needed to power 300 6W light bulbs for one hour. The energy balance over the pilot plant showed that the system required 10% energy of its energy output to produce 1.8 kW. Based on these results, it can be concluded that the pilot plant is effective and a viable technology in SA. Furthermore, produced biogas was clean and with negligible amounts of hydrogen sulphide (H_2S), thus, posing no harm towards machinery and human operators. The biogas consisted of 60% methane (CH_4), 29% carbon dioxide (CO_2) and 94 ppm of H_2S. In evaluating SAs energy potential from current FW, it was found that 297 and 475 GWh of electricity, at 25 and 40% conversion, can be produced, turning on 8 million 6 W lights per hour.

Overall, the study has shown that biogas technology is readily available for South Africans to utilise. The designed biogas plant was very efficient in maintaining favourable digester temperatures and treating FW. The main aim, which was to carry out AD of FW and determine the potential of generating electricity from the biogas produced, was achieved. The knowledge attained in this work is intended to encourage the uptake of FW biogas technology in SA.

5.2 Recommendations

Since biogas technology has been proven to be a reachable and a net energy producer waste treatment solution in South Africa, it's uptake for the treatment of FW and possibly other organic wastes is highly recommended. More should also be done in recovering the liquid and solid digestate as fertiliser for food production, while determining effluent readiness to fertilise. Furthermore, other uses of biogas, such as fuelling a vehicle, may be explored in future. The amount of inoculum added before food digestion and its effect on biogas production and methane yield may be investigated. For a shortened startup in terms of heating up the digester, it is recommended that the heating water be brought to boiling point before heating the digester. Lastly, the showcasing of this technology to the public is recommended for increasing the public's awareness of this technology and potentially, its uptake.