Determining the waste composition profile to optimise biomethane production: A case study for the South African ice cream industry

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PREFACE AND ACKNOWLEDGMENTS

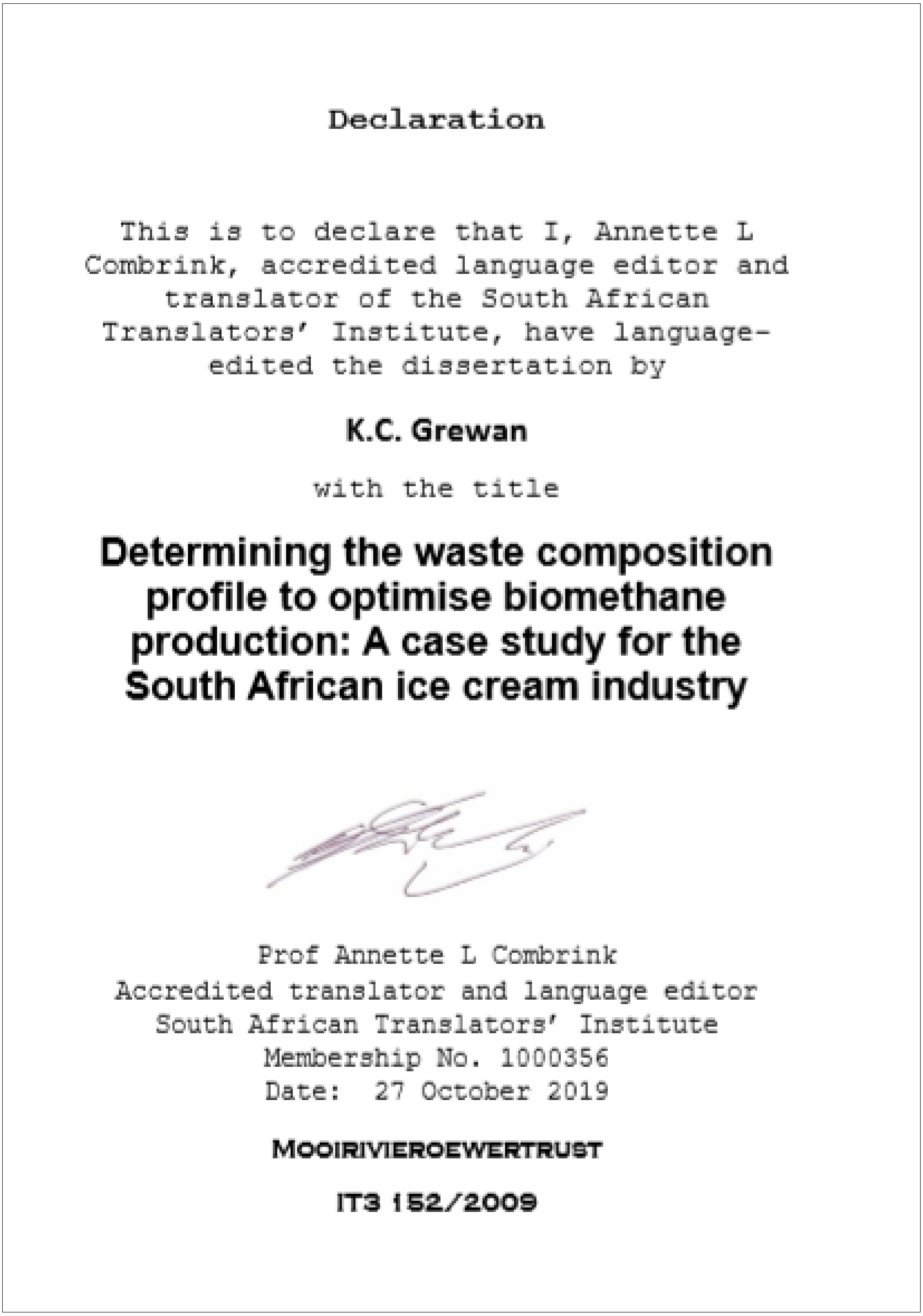
This thesis documents research done focusing on “waste-to-energy” (WtE) with an application on dealing with waste in the ice cream manufacturing process. The study was conducted within the context of two challenges that South Africa is facing – dealing with the impacts of waste and addressing the current energy crisis. The study focused on determining the waste composition profile to optimise biomethane production from various waste components produced at the ice cream factory in South Africa. It has been completed to fulfil the graduation requirements of the Research Unit for Environmental Sciences and Management at the North-West University (Potchefstroom Campus) in 2019.

I would like to give heartfelt thanks to my supervisor for her excellent guidance and support during this process. There have been various and numerous communications received by my supervisor, which served as support throughout this process.

To my parents and sister, they deserve a note of thanks as your wise direction and optimistic words have always motivated me to be better and never give up on my dreams, even the wild ones.

Finally, to my husband, Daniel, thank you for always understanding and giving me the space to better myself by studying further even when it went into late nights and weekends. You are truly amazing, and I appreciate you for being the best partner and motivator during this research process and in life.

PROOF READING CERTIFICATE



Declaration

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Determining the waste composition profile to optimise biomethane production: A case study for the South African ice cream industry

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ABSTRACT

The management of waste is a global concern, especially dealing with issues such as limited landfill airspace and the negative impacts of waste on the environment. To minimise these impacts, the National Waste Management Strategy (NWMS) proposes a waste management hierarchy, where the disposal of waste must be regarded as the last resort. Additionally, the White Paper on Renewable Energy (2003) and the National Climate Change Response White Paper (2011) also highlight the fact that the waste sector, which includes biogas to energy projects, has the potential to mitigate greenhouse gases. Within this context, the research aimed to determine the optimal composition profile of waste from the ice cream industry to produce the most (quantity of) biomethane. A mixed-methods approach was used, where a literature review was combined with laboratory analysis of different waste composition variations. Waste composition variations consisted of ice cream waste only; ice cream waste mixed with ice cream sludge (waste variation 1); ice cream waste mixed with woodchips and ice cream sludge (waste variation 2); and ice cream mixed with wood chips and raw material (waste variation 3). The physico-chemical characteristics and the biomethane production output of the waste variations were determined.

Based on a 28-day analysis, it was found that ice cream waste (only) had the potential to produce biomethane (1894.2±101.1 Nml CH_4/kg VS), similar to results reported in literature for dairy-related wastes. The addition of ice cream sludge, however, slightly improved the biomethane production potential (1965±7.1 Nml CH_4/kg VS). The waste composition variations where wood chips were added produced lower amounts of biomethane (1085.4±43.1 Nml CH4/kg VS and 1024.9±61.6 Nml CH_4/kg VS, respectively). Considering the cumulative biomethane output over a 28-day period, ice cream only waste and waste variation 1 produced similar trends, with biomethane production stabilising on days 18 and 19, respectively. Waste variation 2 showed a rapid increase in biomethane production between days 4 and 10, with biomethane production stabilising on day 13, whereas waste variation 3 already stabilised on day 10. To explain the differences in biomethane production, the correlation coefficient between biomethane output and the physico-chemical characteristics, such as volatile solids (VS), total solids (TS), pH and moisture content, of the waste variations was determined. The only significant positive correlation was found between biomethane production and moisture content, where the waste variations with a higher moisture content produced a higher biomethane output. In conclusion, the results of the study indicated that ice cream waste does have the potential to produce biomethane and biomethane outputs were similar to other dairy waste-related studies. The results suggest that the addition of ice cream sludge, which also contains waste water from the ice cream manufacturing process, has the potential to improve biomethane production.

Keywords: Biomethane, anaerobic digestion, ice cream waste, waste-to-energy (WtE)

ACRONYMS AND ABBREVIATIONS

ABPP	African Biogas Partnership Programme
AD	Anaerobic digestion
AGET	African Green Energy Technology
Al	Aluminium
AMPTS II	Automatic Methane Potential Test System II
ATSDR	Agency for Toxic Substances and Diseases Registry
Btu	British thermal unit
BMP	Biochemical methane potential
C	Carbon
Ca	Calcium
CDM	Clean development mechanism
CGW	Cotton Gin Waste
CH_4	Methane gas
CM	Cow manure
CO	Cobalt
COD	Carbon Oxygen Demand
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
DEA	Department of Environmental Affairs (now known as the Department of Environment, Forestry and Fisheries, DEFF)

DME	Department of Minerals and Energy (now known as the Department of Mineral Resources and Energy)
DST	Department of Science and Technology
DNA	Designated National Authority
EPR	Environmental Performance Reporting
FOS	Volatile Organic Acids (German translated to English)
GC	Gas chromatography
GHG	Greenhouse gas
GJ	Gigajoule
GWh	Gigawatt hour
H	Hydrogen
H_2S	Hydrogen Sulphide
JI	Joint implementation
Kr	Krypton
KENDBIP	Kenyan National Domestic Biogas Programme
LFG	Landfill gas
LFGTE	Landfill gas to energy
LFSGR	Landfill system with gas recovery
m^3	Cubic metre
M2M	Methane to markets
MFMA	Municipal management Finance Act
Mg	Magnesium
MSW	Municipal solid waste

MSWtE	Municipal solid waste to energy
MWh	Megawatt per hour
N	Nitrogen
Na	Sodium
NBMMP	National Biogas and Manure Management Programme
NDP	National Development Plan
NH3	Ammonia
Ni	Nickel
NIR	Near-infrared
NHþ4	Form of ammonia
Nml	Normalised millilitres
NMOC	Non-methane organic content
NPBD	National Programme on Biogas Development
NWMS	National Waste Management System
O	Oxygen
OLR	Organic Loading Rate
OFMSW	Organic Fraction of Municipal Solid Waste
pH	Power of Hydrogen
RDF	Refused Derived Fuel
TA	Total Alkalinity
TAC	Totales Inorganic Carbonate (German to English translation)
TS	Total Solids
UN	United Nations

UNFCCC	United Nations Framework Convention on Climate Change
US EPA	United States Environment Protection Agency
VFA	Volatile Fatty Acids
VS	Volatile Solids
WFPP	Waste-fired power plant
WtE	Waste to energy
WWTP	Waste water treatment plant
Zn	Zinc

DEFINITIONS AND TERMINOLOGIES

Air pollution

"air pollution" means any change in the composition of the air caused by smoke, soot, dust (including fly ash), cinders, solid particles of any kind, gases, fumes, aerosols and odorous substances (National Environmental Management Air Quality Act, Act 39 of 2004).

Anaerobic Digestion

“anaerobic digestion” (AD) is a biological process in which microorganisms break down biodegradable material in the absence of oxygen creating two important products: biogas and digestate (European Biogas Association).

Atmospheric emission

"atmospheric emission" or *"emission"* means any emission or entrainment process emanating from a point, non-point or mobile source that results in air pollution (National Environmental Management Air Quality Act, Act 39 of 2004).

Biogas

“biogas” is the primary product of AD is a methane-rich renewable gas composed of 50 to 65% methane and 35 to 50% carbon dioxide (European Biogas Association).

Biomass energy

biomass energy (from organic matter) can be used to provide heat, make liquid fuels, gas and to generate electricity. Fuelwood is the largest source of biomass energy, generally derived from trees. However, fuelwood is used unsustainably when new trees are not planted to replace ones that are used. Fuelwood derived in this way cannot be properly defined as renewable. Other types of biomass include plants, residues from agriculture or forestry, and organic components in municipal and industrial wastes. Landfill gas is considered to be a biomass source (White Paper on the Renewable Energy Policy of the Republic of South Africa, 2003).

Biomethane

When carbon dioxide and trace gases in biogas are removed, a methane rich renewable natural gas substitute is left in the form of *“biomethane”*. Biomethane can be injected into the gas grid, used as a vehicle fuel or used for combined heat and electricity generation (European Biogas Association).

Greenhouse gas

"greenhouse gas" means gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation, and includes carbon dioxide, methane and nitrous oxide (National Environmental Management Air Quality Act, Act 39 of 2004).

Kyoto protocol

“Kyoto Protocol” is an international agreement linked to the United Nations Framework Convention on Climate Change, which commits its Parties by setting internationally binding emission reduction targets. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005 (United Nations Framework Convention on Climate Change, 2019).

Landfill

“*landfill”* means a system of trash and garbage disposal in which the waste is buried between layers of earth to build up low-lying land (Merriam-Webster, 1903).

Offensive odour

"offensive odour" means any smell which is considered to be malodorous or a nuisance to a reasonable person (National Environmental Management Air Quality Act, Act 39 of 2004).

Organic waste

“organic waste” means waste of biological origin which can be broken down, in a reasonable amount of time, into its base compounds by micro-organisms and other living things and/or by other forms of treatment (Draft National Norms and Standards for Organic Waste Composting, GN. 115 of September 2019).

Refuse Derived Fuel (RDF)

“refuse derived fuel (RDF)” is a fuel produced from various types of waste such as municipal solid waste, industrial waste or commercial waste.

Waste

(a) any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered; (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered; (iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste. (National Environmental Management Waste Act (59 of 2008), as amended)

Waste management activity

"waste management activity" means any activity listed in Schedule 1 or 40 published by notice in the Gazette under section 19, and includes—

(a) the importation and exportation of waste;
(b) the generation of waste, including the undertaking of any activity or process that is likely to result in the generation of waste:
(c) the accumulation and storage of waste;
(d) the collection and handling of waste;
(e) the reduction, re-use, recycling and recovery of waste;
(f) the trading in waste;
(g) the transportation of waste;
(h) the transfer of waste;
(i) the treatment of waste; and
(j) the disposal of waste (National Environmental Management Waste Act, Act 59 of 2008).

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CHAPTER 1. INTRODUCTION

1.1. Background

Solid waste management is the sole provision that almost every metropole provides for its citizens. While service levels, environmental impacts and costs differ dramatically, solid waste management is one of the most imperative services rendered by a municipality. In 2012, world cities generated approximately 1.3 billion tonnes of solid waste per annum (Hoornweg & Bhada-Tata, 2012). This volume is projected to increase to 2.2 billion tonnes by 2025. It is expected that waste generation rates will more than double over the next twenty years in lower income countries. The above mentioned is quite an alarming statement as the global impact of solid waste is rapidly increasing. Solid waste has the potential to generate large quantities of landfill gas, which contains methane, a greenhouse gas (GHG) that is principally impactful in the short-term (Hoornweg & Bhada-Tata, 2012), but may be used for energy production.

The waste management hierarchy (as outlined in the National Waste Management Strategy, 2011) (Figure 1-1) advocates the disposal of waste as a last resort, because of the adverse impacts of waste on the environment, including the generation of landfill gas (LFG). According to the hierarchy, the recovery of energy from waste is preferred to landfill disposal.

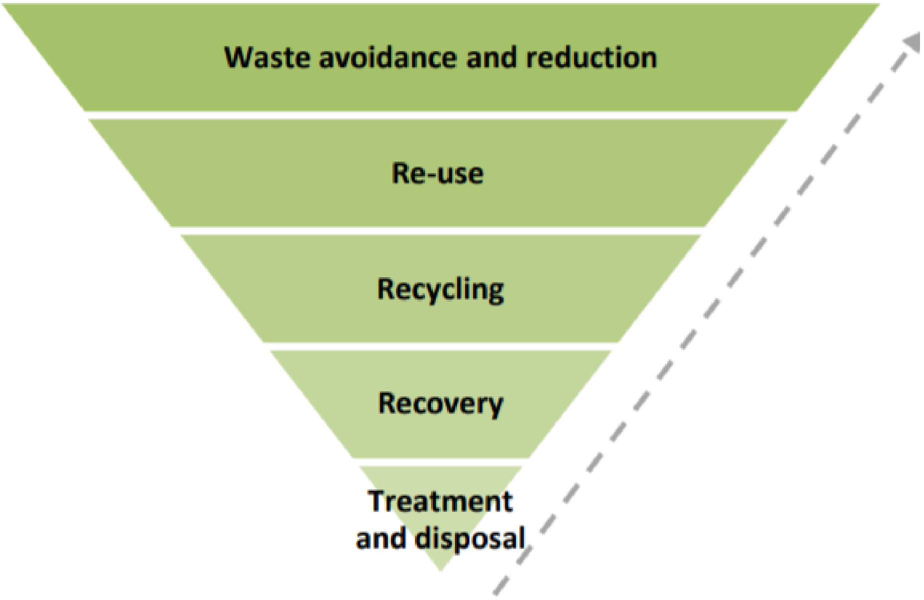

Figure 1-1: The waste management hierarchy, as proposed by the National Waste Management Strategy (DEA, 2011b)

1.1.1. The negative impacts of landfill gas (LFG)

As solid waste decays in landfills, a gas is produced that is approximately 50 percent methane (CH_4) and 50 percent carbon dioxide (CO_2), both of which are GHGs (U.S. EPA, 2011). Methane gas is approximately 21 times worse (21 x CO_2 equivalents) for the atmosphere (in terms of its greenhouse gas impacts) than carbon dioxide (CO_2 is 1 equivalent). Although the concentration of CH_4 in landfill gas (LFG) does differ during different stages, during the methanogenic process concentrations of around 50% are commonplace. LFG will continue to be produced during the entire operational and stabilisation phase of the landfill site, up to thirty years after closure of the site (Strachan *et al.*, 2008).

Historically, LFG was mainly managed because of its CH_4 content, which is explosive when in interaction with certain concentrations of air, as well as to control offensive odours. Minimal focus was placed on the management of LFG as a result of the potential environmental impacts. The requirements for the management of LFG, however, changed in 1997 when the Kyoto Protocol was accepted by mainly European countries to work together to decrease GHG emissions. The Protocol finally entered into force in February 2005, with South Africa being a signatory of the Protocol.

1.1.2. The potential positive impacts of waste-related gas

Article 12 of the Kyoto Protocol defines clean development mechanisms (CDM) and allows developing countries to implement emission-reduction projects, which can earn saleable credits. Lee *et al.* (2009) note that by 2008, the carbon compliance market had reached US$118 billion, being driven by the Kyoto Protocol as well as the EU emissions trading scheme. To this extent, developing countries, which would not have been able to afford such processes in the past, can now afford to implement CDM projects.

Because of the 21 times factor (of CH_4 vs CO_2), LFG-to-energy and other waste-to-energy (WtE) projects are very profitable and prevalent in order to achieve CDM and other carbon trading funding. However, the system to attain a registered project is very time consuming, expensive and complex (Novella, 2014).

WtE is the process of generating energy (electricity or heat) from the treatment of waste, or the processing of waste into a fuel source, or directly from landfill gas - and is a form of energy recovery. Although treatment and energy recovery are seen as less preferred options in terms of the waste management hierarchy (as opposed to avoidance, re-use and recycling) (see Figure 1-1), energy recovery is still deemed to be a good option for the management of waste (DEA, 2011b).

One of the viable WtE options in South Africa is the conversion of *organic wastes* to biogas (and eventually to biomethane) through anaerobic digestion for energy recovery purposes (GreenCape, 2017).

During ideal conditions, one ton of waste can produce 150 - 200 m^3 of biogas. It is noted that - the greater the amount of *organic waste*[1] present, the more biogas is produced by the bacteria during decomposition (Karapidakis & Tsave, 2010). About 60% of the waste currently produced in South Africa is organic, while approximately 40% of it is being landfilled (SAWIC, 2018).

Considering the large quantities of organic waste produced in the country, the conversion of waste to biogas is an option that needs to be considered, instead of landfilling organic waste.

1.2. Biogas to energy

Biogas is a mixture of CH_4 and CO_2 and trace amounts of other gases, naturally produced from the decomposition of organic elements. The biogas can be formed either during landfilling processes (as LFG), aerobic digestion or anaerobic digestion. For the purposes of this study, *anaerobic digestion* will be focused on.

Anaerobic digestion is a biological method for the treatment of organic waste, in the absence of oxygen, which results in the production of methane-enriched *biogas*. When carbon dioxide and trace gases in biogas are removed, a methane rich renewable natural gas substitute is left in the form of *biomethane*. Biomethane can be injected into the gas grid, used as a vehicle fuel or used for combined heat and electricity generation (Zhong *et al.*, 2012).

The process of anaerobic digestion in the context of biogas (and eventually biomethane) production will be focused on in detail in Chapter 4 (Literature review).

Apart from clean energy production, anaerobic digestion technology has other economic, environmental, social and policy advantages compared to landfilling.

1.2.1. Economic advantages of biogas to energy

Waste disposal costs in South Africa are relatively low, when compared to other countries, but becoming higher for particular types of organic waste, such as abattoir waste, which now requires disposal at landfills that meet particular requirements. Economic instruments provided for in terms of the *National Pricing Strategy for Waste Management* (DEA, 2016) have the implication of

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[1] Organic waste includes food waste like ice cream, which this study will focus on.

landfilling becoming more expensive, while other waste management options would be financially more feasible.

Another economic consideration is the price of electricity. Since 2004, the price of Eskom-generated electricity has increased by 300%, and is still subject to inflation (GreenCape, 2017). WtE projects may lead to savings in the long term.

1.2.2. Environmental advantages of biogas to energy

Environmental-related advantages of biogas to energy projects may include:

- Reduction of air pollution and climate change mitigation

  Compared to landfilling, which produces CH_4 emissions in LFG (Refer to Section 1.1) (Zhong *et al.*, 2012).

- Landfilling is reduced

  Anaerobic digestion of organic waste reduces the amount of waste that needs to be disposed to landfill. This has the advantage of preserving airspace for the disposal of other types of waste, and it also decreases the amount of pollution (leachate, emissions, etc.) that is formed as part of the landfilling process (Zhong *et al.*, 2012).

- Clean energy and energy security

  Cleaner energy is produced, when compared to energy produced by coal-fired power stations. Biogas is regarded as a renewable source of energy (GreenCape, 2017). *The energy produced can also be utilised during periods of load shedding, and gas can be stored for later use.*

- Investment in the green economy and infrastructure

  Biogas to energy contributes to the green economy. It creates jobs, and investment in physical infrastructure has multiplier effects in the economy (GreenCape, 2017).

1.2.3. Policy advantages of biogas to energy

By diverting waste away from landfill and considering WtE technologies instead (such as capturing biogas from anaerobic digestion), CH_4 can be captured and prevented from being emitted to the atmosphere, which can decrease CH_4 emissions (compared to landfilling) by between 60 and 90 percent (U.S. EPA, 2011). WtE options may aid in giving effect to Outcome 10 of the *National Development Plan* (NDP) of South Africa for 2030. Outcome 10 consists of several outputs and sub-outputs, and WtE options may contribute to the output focusing on *"reduced greenhouse gas emissions, climate change and improved air quality"* (National Planning Commission, 2012).

Another goal of the NDP is to *"produce sufficient energy to support industry at competitive prices, ensuring access for poor households, while reducing carbon emissions per unit of power by about one-third" (*National Planning Commission, 2012). South Africa is, however, facing an energy crisis, where access to sustained electricity has become problematic over the past ten years. The current energy crisis is quite severe, as there have been rolling blackouts due to load shedding from Eskom. Load shedding is known as a way of handling a condition where the energy demand surpasses the productive capacity of the country. Load shedding is counterproductive (loss of time and capital), therefore alternatives of energy supply need to be found and utilized quickly.

WtE technologies have been identified as one of the renewable energy options for South Africa in the *White Paper on the Renewable Energy Policy of the Republic of South Africa* (DME, 2003). It is regarded as an option with relatively low capital cost and medium running costs.

The importance of WtE projects in South Africa, as it relates to the policy context is elaborated on in Chapter 4 of this dissertation.

1.2.4. Biogas to energy in South Africa

The South African biogas industry is relatively small and emergent when compared to other countries. According to GreenCape (2017), in 2017 there were approximately five-hundred digesters in the country, of which about 40% are located at wastewater treatment works and the other 60% are being used for other purposes. Only a few of these digesters are used for commercial and industrial applications. Opportunities, therefore, exist to develop and leverage this emerging industry.

The *White Paper on Renewable Energy Policy of the Republic of South Africa* (DME, 2003) acknowledges that renewable resources generally operate from an unlimited resource base and can increasingly contribute towards a long-term sustainable energy future. The development of government's renewable energy policy is guided by a rationale that the country disposes of very attractive renewable resources (in the form of waste), and the development of renewable energy projects, such as biogas to energy, is a priority of the South African government.

1.2.5. Factors influencing biogas production

The amount and quality of biogas production may be influenced by factors such as waste composition, moisture content, oxygen content, particle size, temperature, and pH (Agency for Toxic Substances and Disease Registry, 2001), to name a few. These factors are extensively discussed in Chapter 4. Understanding the optimal conditions for biogas (and ultimately, biomethane) production is important for the optimisation for anaerobic digestion of waste. This study has specifically focused on understanding the optimal waste composition profile, as one of the factors influencing biogas production.

1.3. Problem statement and rationale for the study

The waste management issues that the country is grappling with at the moment, coupled with the energy crisis and supporting policy framework, create an enabling environment for the development of WtE technologies. Opportunities exist to research and understand these technologies, also considering the large quantities of organic waste (with the potential to produce energy) which need to be managed and disposed.

An example of one such waste with the potential to produce biogas is *dairy* waste (El-Mashad & Zhang, 2010; Lisboa & Lansing, 2013; Demirel *et al.*, 2004). Dairy farming is the fourth largest agricultural industry in the country and represents 6% of the gross value of overall agricultural production (Mkhabela *et al.*, 2010). Dairy farming and related dairy processing facilities have the potential to produce large quantities of organic waste, in the form of liquids, solids and sludges. This study focuses on dairy-related waste from the Ola Lords View *ice cream factory* in Midrand.

The Ola Lords View factory was commissioned in 2015 and produces approximately 120 tonnes of ice cream waste and sludge per month on average, with up to approximately 200 tonnes of ice cream waste and sludge per month during the peak season of summer. This is a significant amount of waste (with the potential of generating biogas), which is currently disposed to landfill and not being utilized for energy generation. The feasibility of commissioning an anaerobic biodigester for the production of biogas for energy generation purposes is being established.

This study aimed to understand the potential for biomethane production from ice cream waste generated by the Ola Lords View factory, through anaerobic digestion. In South Africa, limited research has been done specifically focusing on ice cream waste, and the optimal waste composition profile for the formation of biogas. It is, therefore, anticipated that this study will add value in terms of knowledge gained with regards to biomethane production from ice cream waste, which could also potentially be extrapolated to other types of dairy-related wastes.

1.4. Research aim and research questions

This research aimed at understanding the *potential* for biomethane production and optimum waste composition profile for biomethane production, by focusing on a specific waste type, namely *waste from the ice cream industry*. The ultimate objective was to determine the optimal *composition profile* of waste from the ice cream industry to produce the most (quantity) biomethane during anaerobic digestion.

The waste composition researched included mainly ice cream waste (finished product) and ice cream sludge, since these wastes are representative of the largest quantities of waste currently being generated by the ice cream factory (refer to Chapter 2). Other related wastes, such as plastic packaging, tubs, lids and wooden sticks are also considered, however, in smaller quantities. The study also aimed to understand the supporting elements (policy, technology, resources, etc.) necessary for the successful implementation of WtE projects, by focusing on lessons learned from elsewhere in the world.

To summarise, the research questions included:

1.4.1 Does waste from the ice cream factory have the *potential to produce biomethane*? (RQ1)

1.4.2 What is the *optimal waste composition ratio/profile* that would produce the most (quantity) biomethane? (RQ2)

1.4.3 What *supporting elements* are necessary for the successful implementation of WtE projects? (RQ3)

To determine whether or not the waste from the ice cream factory has the potential to produce biogas, the composition of the waste needs to be understood. Existing historical data (from 2016 onwards) on waste composition and quantity were used to inform the waste composition variations tested for biomethane production potential.

Although *understanding the waste composition profile* of the waste typically generated by the ice cream factory was not considered to be one of the research questions, it was central to informing the design of the research method to take an informed decision on the waste variations tested for potential biomethane production.

1.5. Delineation of study

The study focused on the bio-methane production potential of *ice cream waste* and certain ice cream waste mixtures (variations), only. Although the findings could be equally applicable to other types of dairy-related waste, this study only focused on these types of waste, because it falls within the scope of work of the researcher and it is a problem which Unilever South Africa aims to solve. The waste streams included in the study were: ice cream, ice cream sludge, wood chips and raw material (ice cream flavouring) (as outlined in Table 3-2) from the Ola Lords View factory in South Africa, only.

During organic waste decomposition processes, various gases are formed. This study, however, only focuses on *biomethane*, because it is the portion of landfill gas which can eventually be converted to energy. Although various technologies are available for WtE, the study mainly focused on *anaerobic digestion*. Biomethane production potential tests were, therefore, performed in a laboratory where anaerobic digestion conditions were simulated, and biomethane potential was determined using the *biochemical methane potential assay* as explained in Section 3.3.2 of this dissertation.

The study includes waste-related data from *2016 to 2019* only. The Ola Lords View factory commenced with ice cream production pilots in 2015, but only started to consistently produce ice cream in 2016. Therefore, data form 2016 onwards should give an accurate reflection of the quantities and relative composition of the waste under investigation

1.6. Limitations of the study

The limitations of this study include sample size. The area sampled (one ice cream factory in South Africa) is relatively small. The facility is, however, regarded as indicative of the waste that would typically be produced by an ice cream factory, and may be deemed to be reflective of waste and its biomethane production potential for other similar factories.

The factory produces 200 tonnes of ice cream waste per month during the peak season of summer. During May to July (winter months), the factory is normally shut down for winter. The waste generation data, therefore, provide insights into waste being produced during nine months of the year, and not a consistent twelve-month year.

The factory was opened in 2015, with waste generation data being recorded from 2016 onwards (only three and a half years' worth of data), and therefore limited data are available on the average quantities of waste being produced per year. The waste variations were also only four, therefore this is a limited range.

Furthermore, in Africa there are few dairy factories that record their waste, which makes comparative analysis difficult.

As far as the literature review of biogas generation is concerned, many of the reports on national levels of biogas produced are outdated or do not have accurate details about the biogas projects in South Africa.

Although the waste management hierarchy advocates the avoidance, minimization, re-use and recycling of waste as preferred alternatives to treatment and energy recovery, this study does not aim to address the implementation of these strategies by the Ola Lords View ice cream factory. The investigation of these strategies (as an alternative to treatment and recovery) are useful, and it is recommended (in Chapter 6) that these options need to be researched further. The aim of this study is to understand the biomethane production potential of the waste currently generated by the ice cream factory and to understand the optimal composition profile of the waste being disposed, to ultimately determine the viability of energy production from ice cream waste in future.

1.7. Outline of dissertation

This segment of the dissertation presents and describes the chapters of the study and highlights several topics that are covered. This dissertation comprises six chapters. Chapter 1 is the introductory chapter which provides a background to the impacts of LFG and biogas to energy opportunities including the problem statement and research aim and objectives. Chapter 2 contextualizes the case study, namely ice cream manufacturing by Ola Lords View Ice Cream Factory. Chapter 3 of this study details the research design and methodology as well as the ethical considerations and limitations, while Chapter 4 reviews the literature on WtE from a global, continental, national and regional level in the dairy industry waste to energy context. Chapter 5 presents the results and discussion, while Chapter 6 provides conclusions on the findings and offers recommendations, mainly for further research. Figure 1-2 shows an outline of the dissertation.

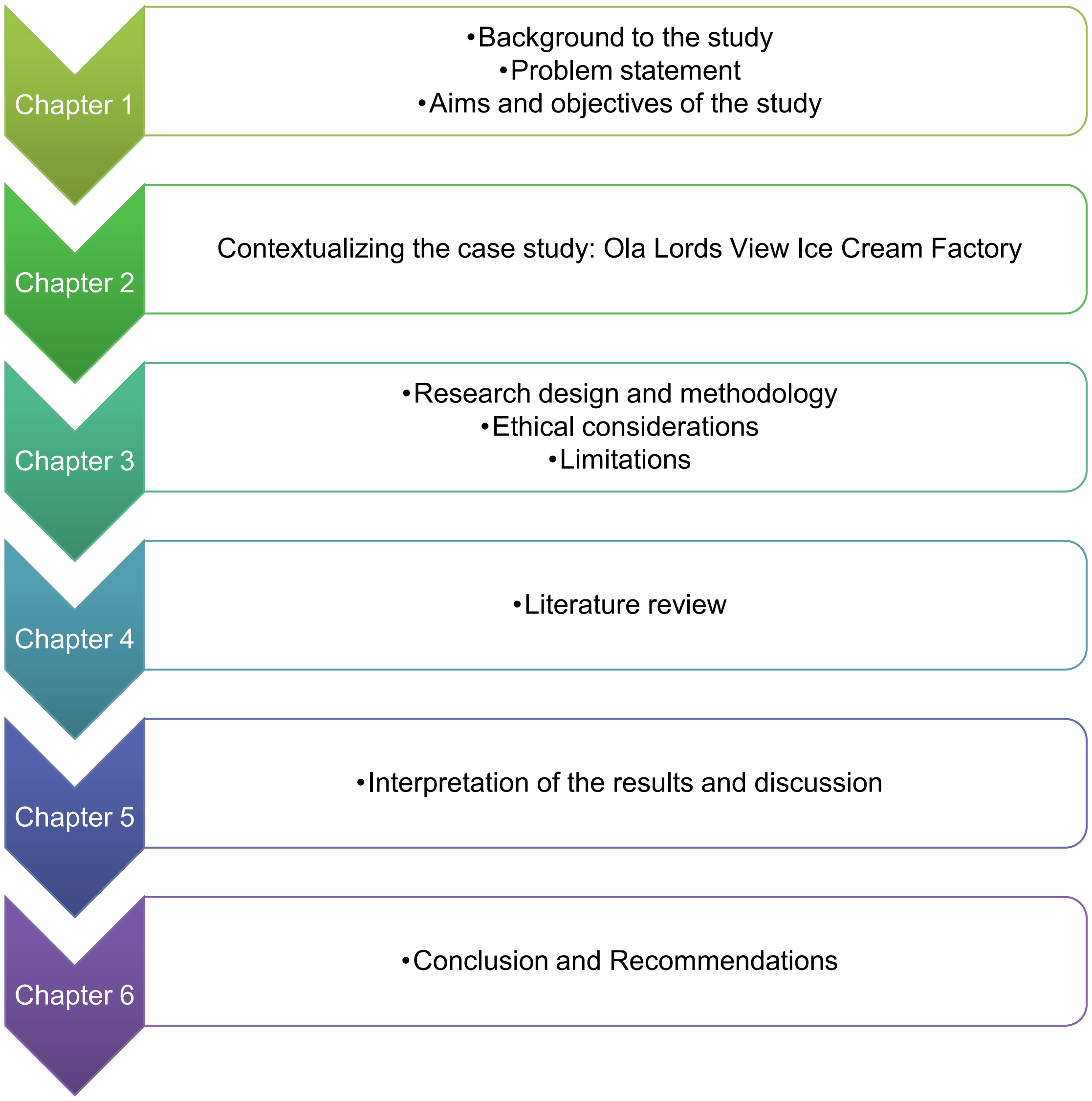

Figure 1-2: Outline of this dissertation

1.8. Chapter summary

This chapter outlined the introduction to this study, together with the rationale, indicating the need for this research. The research questions were outlined to provide the reader with an indication of what the study aims to investigate.

The next chapter (Chapter 2) will provide an overview of the case study used for this research, namely the Ola Lords View Ice Cream Factory, while Chapter 3 will explain the research methodology that was employed during the study, which will be followed by a detailed literature review (in Chapter 4).

CHAPTER 2. CONTEXTUALISATION OF THE CASE STUDY: OLA LORDS VIEW ICE CREAM FACTORY

2.1. Introduction

The aim of this chapter is to provide an overview of the ice cream manufacturing process at Ola Lords View ice cream factory, with the objective of contextualising the study. The aim of this chapter *is not* to provide an in-depth understanding of the ice cream manufacturing process and related waste, but rather to give a brief description of the process to provide the background against which the research questions were formulated and researched.

Unilever South Africa commissioned its first state of the art ice cream factory in Africa in 2015. The factory is situated in the Lords View Industrial Park, Midrand. The Lords View factory is one of forty Unilever ice cream factories across the world.

2.2. An overview of the ice cream manufacturing process

The following sections provide a brief overview of the ice cream manufacturing process, mainly focusing on the production processes, as well as the waste generation and waste management aspects of ice cream manufacturing. Section 2.2.1 provides a basic explanation of the ice cream manufacturing process, while Section 2.2.2 aims to provide an understanding of the waste generation and management processes.

The information provided is from Ola ice cream factory and the author's working knowledge of the ice cream manufacturing process. Therefore, no academic citations are provided for the information provided in this chapter.

2.2.1. The ice cream manufacturing process

The ice cream production process is simple; however, it does get more complex when adding different flavours or when manufacturing a variety of shapes and sizes. There are twenty-five steps - from receiving the raw materials to distribution of the final ice cream product. Figure 2-1 provides a schematic overview of the ice cream manufacturing process, with the main steps and sub-steps of each process. The process starts with the main ingredients being mixed, after which it goes into a chill room. The water portion is heated and then dosed with the correct mix of ingredients. It is then further blended and goes through the homogenizing and pasteurizing processes. It is chilled again, and flavours are added, before it goes into the ageing phase. The mix is frozen again and sent into the factory to be filled into tubs. The tubs are lidded and date coded and transferred to a tunnel to be hardened. The final product is packed in cases and sent to be palletized and dispatched for distribution in a cold storage.

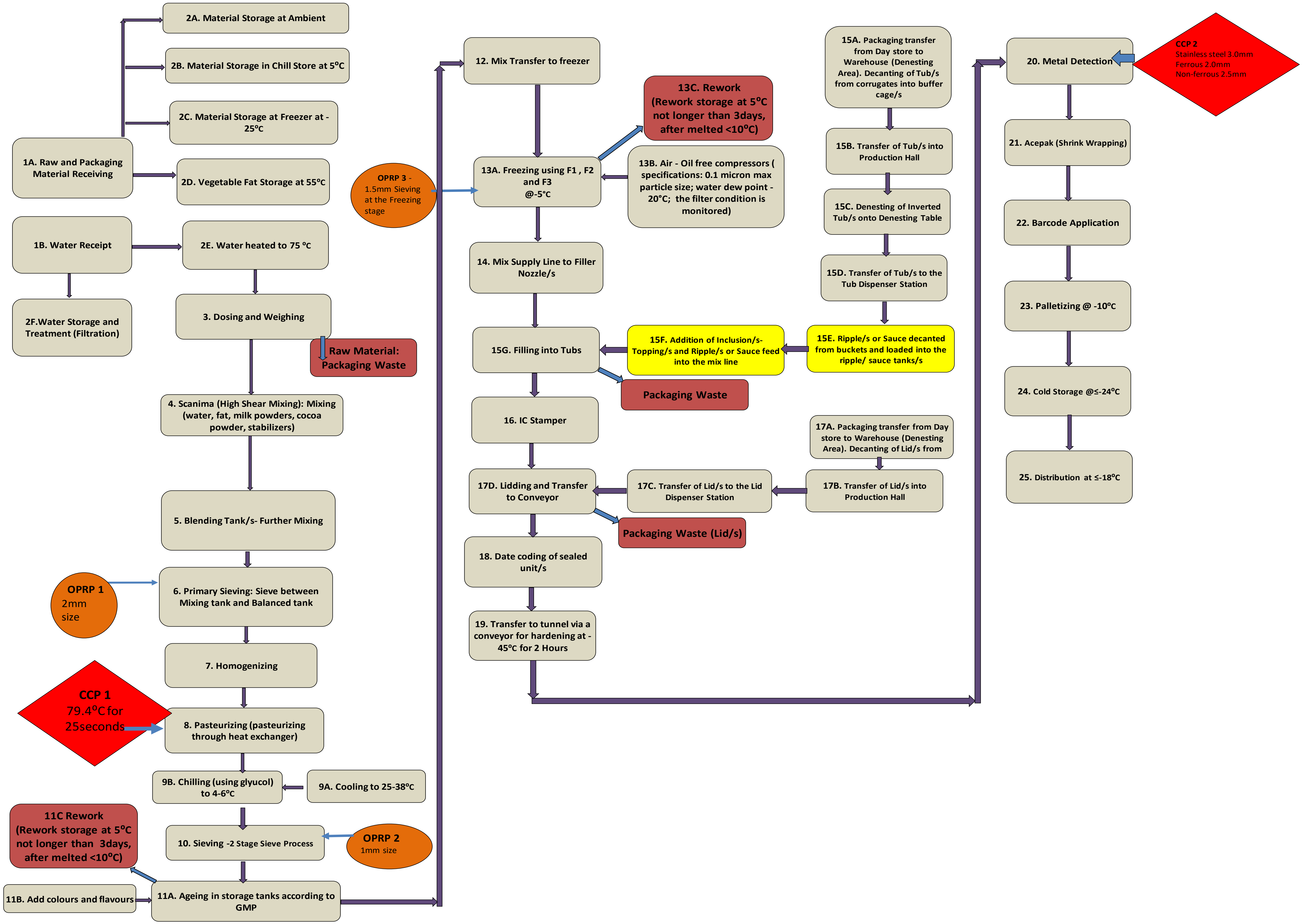

Figure 2-1: **Schematic representation of the ice cream manufacturing process**

The sub-sections (below) provide a description of the following main steps of the ice cream manufacturing process:

- Storage of raw materials;
- Scanima mixing and further blending;
- Homogenization;
- Pasteurizing;
- Freezing;
- Ageing and adding colours;
- Hardening; and
- Palletizing and packaging.

2.2.1.1. Storage of raw materials

Raw materials, such as sugar, vegetable fat, water, milk powder, cocoa powder and flavouring, are at ambient temperatures, viz. 5ºC, -25ºC and 55ºC, depending on the type of raw material. The specific storage temperatures are controlled to preserve the raw materials. A relatively small percentage of raw materials ends up being waste (<3.5%, refer to Table 2-1). Waste from the storage phase is usually due to products not being kept at the correct temperatures (due to operational errors or becoming wet or damaged during off-loading processes) or when the raw products received from suppliers are not up to standard. When incorrect material is received from suppliers, it is rejected and sent back to the supplier to dispose of.

2.2.1.2. Scanima mixing, further blending and sieving

Scanima mixing is a high-shear, high-speed mixing method, where water, fat, milk powders and cocoa powder. The sieving operation ensures no solid material passes through the blending process as this is part of the food quality and safety standard.

After Scanima mixing, the ingredients are further mixed in a blending tank. Waste from the mixing and blending process emanates mainly from ingredients which get stuck to the mixing and blending tanks. Residues are removed during a washing and rinsing process after every new product is mixed and dirty process water goes to the on-site effluent treatment plant (where it is treated to municipal standards), before the water is discharged into the sewer system and the solids are removed by the waste service provider and become part of the ice cream sludge waste stream.

2.2.1.3. Homogenization

Homogenizing is the phase where milk is processed whereby the fat droplets are blended and the cream does not separate to form a homogenous mixture. Waste from the homogenization process is mainly from the vegetable fat and milk which does not mix correctly and therefore needs to be disposed of due to food safety and quality processes.

2.2.1.4. Pasteurizing

Pasteurization entails the fractional sterilization of the mix to make it safe for consumption, and to improve and sustain its (food) quality. Pasteurizing occurs through a heat exchanger where the ice cream is heated to 79.4 ºC for 25 seconds. Waste from the pasteurization process is mainly generated when the temperatures in the heat exchanger is not well controlled and the mixture gets overheated or not heated sufficiently. The product then needs to be discarded, because it does not meet the specifications for food sterilization standards.

2.2.1.5. Freezing

After pasteurization, the mix is cooled to between 25 ºC to 38 ºC, after which it is chilled to between 4 ºC and 6 ºC, using glycol. Minimal waste is expected from the freezing process.

2.2.1.6. Sieving

The sieving operation is a food safety standard implemented to ensure no foreign material solids pass through the next stages.

2.2.1.7. Ageing and adding colours

Ageing entails thawing the mix and then cooling it down, before freezing again, thus allowing it to partially crystalize which allows the protein stabilizers time to hydrate. This phase improves the whipping properties of the mix. Also, colours and flavours are added during this phase. Waste is produced in this phase if the wrong colours and flavours are added or if the colours and flavours are outside food quality and safety specifications. If the mix is vanilla flavoured it can be reworked and blended into other flavours, however, if it is any other flavour the entire mix is discarded.

2.2.1.8. Hardening

The mix is transferred into a freezer at -5ºC and then transferred into tubs (with inclusions) and sealed with a lid. The tub is transferred into a tunnel via a conveyor for hardening at -45ºC for 2 hours. The hardening process changes the mix from a semi-solid to a solid consistency through the continual freezing process in the tunnel. If the product does not harden sufficiently, it cannot be re-hardened as it will create inconsistencies and heat shock in the tubs. The entire tub with ice cream will be discarded.

The metal detector process ensures that no metal is found in this process. There have been limited incidents of bolts from the machinery being found in ice cream. If metal detected, the entire ice cream batch is discarded as waste ice cream. The machinery is then washed and inspected to ensure that there are no loose metal pieces.

2.2.1.9. Palletizing and packaging

After the tubs have been filled and are fully frozen in the centre, they are packed in shrink wrapping and palletized at -10 ºC to keep the mix solid. It is then stored and transported to the distributors at -20 ºC. If the palletizing area is not cold enough, the entire product could get heat shocked and would need to be discarded as finished product waste.

2.2.2. Waste management

Waste may be generated during each of these processes, as explained above. The processes generating the largest quantities of waste are mainly the Scanima mixing, pasteurizer ageing and packaging phases. Although the aim of the study was not to understand the reasons for the generation of waste, nor its exact quantities, the next sections aim to provide an understanding of the waste generation and management processes at the ice cream factory, to inform the overall research design and to contextualize the discussion of the results of the research.

As seen in the previous section, waste is generated during the ice cream manufacturing process due to incorrect ingredient mix, incorrect temperature being achieved, machine failure and product quality issues. Waste types include raw materials (water, vegetable fat, milk powder, sugar and cocoa powder), ice cream (as a finished product) and ice cream sludge, plastics, wood, glass, cardboard and paper, metals, as well as laboratory chemicals.

2.2.2.1. Waste composition and waste quantities

The factory was commissioned in 2015. The waste generated in 2015 is, however, not considered to be reflective of the ice cream manufacturing process, since mostly trials were done in 2015, with limited actual production of ice cream.

A summary of the types and quantities of waste being generated by the ice cream factory from 2016 to 2019 (month to date) are provided in Table 2-1. The waste type and quantity records were derived from Unilever’s global Environmental Performance Reporting (EPR) system. The system requires the input of monthly waste volumes, which is derived from daily reports of waste per line. The ice cream waste is measured daily at the line (as an indication of operational efficiency), while the other waste streams (such as plastics, wood, paper, etc.) are recorded in the waste area (using a scale). Waste quantities are verified at the gate of the facility (on the weighbridge) and final weighting is done at the end-recyclers and landfill weighbridges. These numbers are verified weekly to ensure that the correct data is captured and reported.

Waste generated from 2016 to 2018 and 2019 (month to date) are displayed in Table 2-1. The table provides an overview of the total amount of waste (in tonnes) produced per waste type per year.

The information provides insights into the quantities and composition of waste generated, which is important for the design of the research methodology, as far as determining the most probable waste composition profiles of the factory. The information in Table 2-1 was used to inform the three waste variation types subjected to laboratory analysis (as explained in Chapter 3, Table 3-2).

The waste composition and quantity data indicate that a large quantity of organic waste (approximately 75 to 85% of the total waste) is being generated at the factory, thus showing a relatively high potential of biogas generation.

Table 2-1: Total tonnes of waste produced by the factory per year, per waste type

Type of waste	Waste generated in 2016 (tonnes)	% of total	Waste generated in 2017 (tonnes)	% of total	Waste generated in 2018 (tonnes)	% of total	Waste generated in 2019 month to date (tonnes)	% of total
*[2]Raw materials	41	1.6%	66	3.1%	65	2.9%	16	2.5%
**[3]Ice cream sludge	209	7.9%	161	7.6%	85	3.8%	80	12.5%
**Ice cream finished product	2268	85.8%	1640	77.4%	1770	79.1%	510	79.7%
Non-recyclable plastic	20	0.8%	86	4.2%	56	2.5%	8	1.3%
Recyclable plastic	47	1.8%	56	2.6%	50	2.2%	15	2.3%
Paper	25	0.9%	2	0.1%	5	0.2%	0.5	0.1%
Cardboard	16	0.6%	98	4.6%	161	7.2%	5	0.8%
Wood	15	0.6%	15	0.1%	7	0.3%	2	0.1%
Glass	0	0%	0	0.1%	1.3	0.1%	0	0%
Metal	2	0.04%	1	0.1%	35	1.6%	1	0.2%
Laboratory chemicals	0	0%	5	0.1%	1.7	0.1%	2.8	0.4%
Total	2643		2130		2237		640.3	

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[2] *Raw materials are the ingredients for the ice cream (sugar, vegetable fat, water, milk powder, cocoa powder and flavouring)

[3] **Waste types with a relatively high anticipated potential to generate biogas (because of its organic content) are highlighted in grey.

2.2.2.2. Current waste management practices

The current waste management practices employed by the ice cream factory are explained in the sub-sections below.

2.2.2.2.1. Storage of waste

The waste ice cream is brought to the waste yard in trolley bins and the packaging material is brought in plastic bags. The ice cream is pumped from the bins into a holding tank with a capacity of 30 kilolitres. Once the tank has reached its capacity, the waste ice cream is removed by a super sucker for disposal. The packaging material is sorted into recyclable grades of plastic and non-recyclable plastic and it is baled for transportation (either for disposal, for non-recyclables, or for recycling).

Medical and laboratory waste (from the on-site clinic and microbiological laboratory) is stored in medical bins in the area of use. The wood pallet and the cardboard waste are sorted into categories according to their condition (good and scrap) in a secondary waste storage area.

The ice cream sludge waste mainly emanates from washing and rinsing processes. Water from these processes is treated at the effluent treatment plant. The ice cream sludge waste that cannot be treated or processed is removed from the treatment plant and stored in a skip in the waste yard.

2.2.2.2.2. Transportation of waste

The ice cream (finished product) waste and ice cream sludge waste is transported for disposal in a 30-kilolitre super sucker truck by authorised waste operators, every second day. The remaining non-hazardous waste is transported on a flatbed truck, either for disposal at the general waste landfill site, or for recycling. Hazardous waste is transported and disposed of by an authorised waste operator by means of incineration.

2.2.2.2.3. Waste re-use and recycling practices

The recyclable waste is recycled off-site. Cardboard and wooden pallets, which are in good condition, are re-used on-site. The non-recyclable plastics are taken to a refuse-derived fuel facility. The ice cream waste is transferred to a pig farmer; however, this is currently proving an unsustainable solution, due to the large quantities and variations of ice cream waste being generated.

2.2.2.2.4. Disposal of waste to land

All non-hazardous and non-recyclable waste are currently going to landfill for disposal. Most of the waste goes to the Klinkerstene landfill. The potential to harness biogas from organic waste at the Klinkerstene landfill site is currently under consideration. Unilever is considering the establishment of an anaerobic digester for the conversion of dairy-related waste to energy in the future. This research aims to inform the management of Unilever's decision on whether to proceed with the establishment of an anaerobic digester in future.

2.3. Concluding remarks

Although the waste management hierarchy advocates the avoidance, minimization, re-use and recycling of waste as preferred alternatives to landfill disposal, this study does not aim to address the implementation of these strategies by the Ola Lords View ice cream factory. The investigation of these strategies (as an alternative to landfilling) is useful, and it is recommended (in Chapter 6) that these options need to be researched further.

The aim of this study is to understand the biomethane production potential of the waste currently generated by the ice cream factory and to understand the optimal composition profile of the waste to generate biomethane during anaerobic digestion.

The research methodology (Chapter 3) and the literature review (Chapter 4) must therefore be read with the aim of the research in mind.

CHAPTER 3 METHODOLOGY

3.1. Introduction

The purpose of this study was to determine the optimal composition profile of waste from the ice cream factory to produce the most (quantity) biomethane during anaerobic digestion. A multiple methodology approach was used, where data was gathered by means of literature review and laboratory analysis and analysed using basic statistical analysis.

3.2. Research design and data collection

A mixed-method approach was used to conduct the research (refer to Table 3-1). Mixed methods research design, according to Creswell (2003), is the concept of mixing different methods to answer the research question(s). It is known as "multi-method matrix" to observe various approaches to data collection in a study. Both quantitative and qualitative methods were utilized for this study (refer to Table 3-1) because there is a mixture of information being acquired.

Table 3-1: The methodologies employed to answer each of the research questions of the study

Research question	Methodology used	Rationale
Does the waste from the ice cream factory have the *potential to produce biomethane during anaerobic digestion*? (RQ1)	1. **Literature review** of similar studies done elsewhere in the world. 2. **Laboratory analysis** of the characteristics of the ice cream waste.	1. Literature review was used to gain an in-depth understanding of the factors or conditions where biogas (and eventually biomethane) would form during anaerobic digestion. The literature review, specifically focused on organic waste (and where possible, diary waste) to make a link with the current study. 2. The ice cream waste (only) was analysed through a biochemical methane potential (BMP) test to understand its composition and characteristics, to ultimately determine if the composition and characteristics of the ice cream waste are optimal for biomethane production.
What is the *optimal waste composition ratio* that would produce the most quantity of biomethane during anaerobic digestion? (RQ2)	1. **Literature review** of similar studies done elsewhere in the world relating to production of biogas during anaerobic digestion. 2. **Laboratory and statistical analysis** on different waste composition variations (based on historical data of the typical waste composition expected from the Ola ice cream factory) to determine the quantity of landfill gas produced by each of the waste composition variations	1. Literature review on previous diary to energy plants (mainly anaerobic digestion) and how they optimise diary wastes to produce biomethane that can be converted to energy. 2. Laboratory and statistical analysis on three variations of waste compositions. The three variations were determined based on existing historical data on the typical composition of waste generated by the ice cream factory (refer to Chapter 2, Table 2-1), (considering waste with the likelihood to produce biogas). The quantity of the biomethane produced by each of the waste composition variations was determined, using the BMP test to understand which of these produce the *most (largest quantity)* of biomethane.

Research question	**Methodology used**	**Rationale**
What *supporting elements* are necessary for the successful implementation of WtE project? (RQ3)	1. **Literature review** of similar WtE studies done elsewhere in the world relating to production of biogas (mainly during anaerobic digestion, but also including other WtE technologies).	1. Literature review focusing on lessons learned from other countries, mainly focusing on success factors of WtE plants.

3.2.1. Literature review

The literature review aimed to identify historical data and research on biogas generation, and waste to energy plants to understand the optimum conditions for biogas generation, with a specific focus on waste composition. Special emphasis has been placed on literature on dairy-related wastes to provide comparative examples for the current study, which was focused on waste from the ice cream industry. The purpose was also to identify the key concepts of biogas production (mainly from anaerobic digestion) to use it as “lessons learned” for application by the ice cream factory in Midrand, South Africa.

Historical and methodological literature review have been utilised by researching global and African biogas generation and management. These include studies by Masood (2013), Novella (2014) and Gowing (2001), amongst others. The literature review also considered the challenges of certain countries with funding of these projects as well as the success of others.

The main aim of the literature review was to:

- Understand the *process* of biogas, and eventually biomethane, production from anaerobic digestion;
- Understand whether dairy waste, more specifically ice cream waste, has the *potential to produce biomethane* and to understand the *optimum conditions* for the production of biomethane; and
- Establish *global trends, success factors and challenges* of WtE projects to inform the current study.

The literature review also informed the *methodological design* of the study, based on methods used elsewhere in the world to answer the question regarding biogas production potential.

Chapter 4 of this dissertation provides the full literature review.

3.2.2. Laboratory analysis to determine biomethane production potential

Laboratory analysis were used to address the research questions:

1. Does the waste from the ice cream factory have the *potential to produce biomethane during anaerobic digestion*? and
2. What is the optimal *waste composition ratio* that would produce the most (largest quantity of) biomethane during anaerobic digestion?

3.2.2.1. Laboratory test options for determining biomethane production potential

Various methods exist for determining biomethane production. The sections below provide an overview of the methods available and give a description of the methodology used for this study.

3.2.2.1.1. Near-infrared (NIR) spectroscopy

Near-infrared (NIR) spectroscopy is a valuable means to quantify compounds in pharmaceutical, food, and agricultural industries (Ward, 2016). Lately, it has emerged as a simple and inexpensive alternative to several laboratory methods for the quantification of BMP (Ward, 2016). The method has been used in combination with sophisticated chemometrics to determine BMP (Bekiaris *et al.*, 2015). The NIR spectroscopy method is sensitive to C-H, N-H, and O-H bond interactions and can be measured directly (Ward, 2016; Godin *et al.*, 2015).

3.2.2.1.2. The Envital® kit

Recently, Bellaton *et al.* (2016) introduced a quick assay based on fluorescence, the Envital® kit, to estimate anaerobic biodegradability of sewage sludge. This is an instrument still in early stages of development. The assay produces results in 48 hours, using a fluorescent redox indicator. Comparison of the results with Automatic Methane Potential Test System II (AMPTS II) confirmed the estimated values of BMP according to an uncertainty limit of 25% (Bellaton *et al.*, 2016).

3.2.2.1.3. Chemical composition analyses

The feedstock chemical characteristics such as the chemical composition (lignin, cellulose, hemicelluloses, starch, total soluble sugars, proteins, and lipids) can predict the gas generation by AD (Godin *et al.*, 2015). Chemical composition analysis is applicable in cases where the elemental composition of the substrate is unknown. This can be done economically within a short period of time (Godin *et al.*, 2015).

3.2.2.1.4. Chemical oxygen demand (COD)

Chemical oxygen demand (COD) indirectly measures the amount of organic matter, and for that purpose, it can be applied to approximate the CH_4 yield of biomass substrate (Forgacs, 2012). This method assumes that 1 mole of methane requires 2 moles of oxygen to oxidise carbon to carbon-dioxide and water. Every gram of methane is thus equivalent to 4 grams of COD (Forgacs, 2012).

Although the methods mentioned above have their advantages and could be used to determine biomethane production potential with relative accuracy, the biochemical methane potential (BMP) test was used to determine biomethane production potential during this study. The BMP test is the most commonly used technique to determine biomethane production potential in South Africa and ascertains the effectiveness of the AD process and the biodegradability of the substrate(s) (Esposito *et al.*, 2012). The BMP test provides significant information that can be used to develop mathematical models for prediction of biomethane production from different feedstocks (Angelidaki *et al.*, 2009; Esposito *et al.*, 2012).

3.2.2.1.5. The biochemical methane potential (BMP) test

The BMP test has several variants and despite the wide use of the BMP test (and efforts to standardize the test), no commonly accepted experimental procedure yet exists (Esposito *et al.,* 2012).

The universal principle of the conventional BMP test is to mix an organic feedstock with an inoculum in distinct operational conditions and physically quantify the gas produced by volumetric methods. The biogas composition is determined by gas chromatography (GC) (Esposito *et al.*, 2012). BMP values are assumed as either the sample volume (m^3 CH_4 m^{-3} sample), sample mass (m^3 CH_4 kg^{-1} sample) or sample organic content (m^3 CH_4 kg^{-1} COD) (Zaman, 2010). The conventional BMP test is generally questioned to be time wasting and resource consuming, although it is simple, repeatable and comparatively inexpensive (Rodriguez, 2011; Esposito *et al.*, 2012).

In an attempt to improve on the conventional BMP test, new instruments have been created to analyse the AD process as well as biogas yield and composition. An example of such an instrument is the Automatic Methane Potential Test System (AMPTS) developed by the Bioprocess Control Sweden Company (Shi, 2012). Although the AMPTS removes CO_2 and other acid gases from the biogas before estimating the CH_4 yield, the instrument provides for the basic principles of the conventional BMP test. Methane production is directly measured in-line by means of liquid displacement and buoyancy methods. The AMPTS provides high quality data with minimum labour inputs (Shi, 2012).

3.3. Description of the biochemical methane potential (BMP) test used for this study

The automated BMP test was used to determine biochemical methane production potential during this study. The method was chosen because of its wide use in South Africa, and because it is regarded as an accurate method, providing high quality of data, while reducing time and labour inputs.

All tests were performed using AMPTS II from Bioprocess Control, Sweden. Biochemical methane is measured through water displacement using measurement cells (C) that give a signal for approximately every 10 ml of produced gas. Temperature and pressure sensors are used to normalize the gas volume to standard conditions (i.e. 0 °C, 1 atm. and dry gas) at each measurement point. The BMP test outputs data like the pH value, TS/VS value and moisture content value. An inoculum was first used as the baseline; and thereafter ice cream waste only and three other waste composition variations (outlined in Table 3-2) were tested. The waste composition variations (Table 3-2) were informed by historical data on the waste types, composition and quantities of waste produced by Ola Lords View from 2016 to present (Chapter 2, Table 2-1[4]).

Table 3-2: The variations of waste composition analysed for their biochemical methane potential

Ice cream only waste	**Waste composition 1**	**Waste composition 2**	**Waste composition 3**
100% ice cream	60% ice cream and 40% ice cream sludge	60% ice cream and 20% sludge and 20% wood chips[5]	60% ice cream and 20% raw materials and 20% wood chips
Justification: To determine whether the ice cream (only) waste has the potential to produce biomethane and to have a baseline BMP value to compare the other three waste variations to.	**Justification:** Historical data on waste type and quantity (Table 2-1) indicated that ice cream waste constitutes 80% (on average) of the total amount of waste generated. The second largest amount of waste is ice cream sludge. A 60/40 ratio of ice cream to sludge was therefore tested.	**Justification:** Waste composition 2 suggests adding wood (organic) waste to the waste mixture, to determine whether the presence of wood will influence the biomethane production potential. The addition of wood chips may increase (bulk) the amount of waste which could be reasonably expected to produce biomethane.	**Justification:** The addition of wood to the mixture is similar to the justification provided for mix 2. Waste composition 3 also suggests adding raw materials (such as sugar, cocoa powder, milk powder and vegetable fat) to the mixture, to determine how it influences the biomethane production potential. The addition of raw materials may increase (bulk) the amount of waste which could be reasonably expected to produce biomethane.

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[4] The data in Table 2-1 does not form part of the results of the study (since it is not linked to any of the research questions). It, however, informed the composition of the three variations of waste mixtures (Table 3-2) that were subjected to the BMP test, to determine the optimal ice cream waste composition ratio.

[5] For preparing mixtures with wood chips, the wet wood chips were first dried, and milled to a particle size of < 0.8 mm. This allows the particles to be digestible through the AD process.

Because the largest (by weight) amount of waste generated is ice cream (product after manufacturing), it is proposed that all of the waste composition variations should consist of majority ice cream, mixed with other waste types to: (1) increase the volume/amount of waste and potentially the amount of biomethane produced and (2) simulate a realistic mixture of ice cream and other wastes, which is typical of waste expected from the ice cream factory.

Each of the samples were analysed in triplicate to determine the their physico-chemical characteristics and average biomethane production values and standard deviation. All tests were conducted by the Agricultural Research Council – Agricultural Engineering, Bioenergy Lab. The methodology followed is outlined in the sub-sections below.

3.3.1. Determining physico-chemical properties

To determine the optimal waste mixture to produce the largest quantity of biomethane, four different samples were tested (refer to Table 3-2): (i) ice cream waste only; (ii) 60% ice cream, 40% ice cream sludge; (iii) 60% ice cream and 20% sludge and 20% wood waste (chips); (iv) 60% ice cream and 20% raw materials and 20% wood waste (chips). The justification for choosing these mixtures are provided in Table 3-2.

The physico-chemical properties of all the samples were determined by the Agricultural Research Council – Agricultural Engineering, Bioenergy Lab. The laboratory tests included determination of pH and the moisture content (total amount of moisture in a sample). The total solids (TS) and volatile solid (VS) contents were measured in accordance with standard methods (Sluiter *et al.*, 2008a and Sluiter *et al.,* 2008b); while pH, FOS and TAC values were determined with an Automatic Potentiometric Titrator (AT1000 Series Potentiometric Titrator). The FOS/TAC ratio is an indicator for assessing fermentation processes. FOS/TAC is a German abbreviation, commonly used for VFA/TA (English). FOS or *Volatile Fatty Acids* (VFA) are expressed in equivalent milligrams of acetic acid per litre, while TAC or Total Alkalinity (TA) is expressed in mg equivalent of calcium carbonate per litre.

It is important to note that, after the samples had been digested, they were originally measured for FOS/TAC; however, the results did not consistently stay within the range that was measurable with the laboratory equipment and were therefore not reported as part of the results of this study.

3.3.2. Determining the biochemical methane potential (BMP)

A 28-day BMP test was conducted on all waste variations. Inoculum[6], used to introduce microorganisms to the anaerobic digestion process, was pre-incubated at 37ºC for 5 days in order to deplete the residual biodegradable organic material present in it. Angelidaki *et al.* (2009) and Holliger *et al.* (2016) recommend pre-incubation for 2 to 5 days before starting a BMP test to reduce the amount of gas contributed by the inoculum in BMP tests. Inoculum preparation is one of the most important BMP test factors, having the ability to significantly influence results.

Sodium hydroxide (reagent grade 97%, pellets, Cat. No. 221465, Sigma-Aldrich) was used for the preparation of 3 M alkaline solution for CO_2 scrubbing. A 0.4% Thymolphthalein pH indicator solution was prepared by dissolving the dye powder (2',2''-Dimethyl-5,5''-di-iso-propylphenolphthalein, dye content 95%, Cat. No. 114553, Sigma-Aldrich) in a mixture containing 10% water and 90% ethanol (ACS reagent 99.5%, Cat. No. 459844, Sigma-Aldrich).

CO_2/N_2 gas mixture (25%/75%) (from Air Liquide, South Africa) was used to obtain anaerobic conditions before the BMP preparation phase.

The water bath and water displacement using measurement cells require Type I (ultra-pure) water, which was produced by Easy - ASTM Type I ultra-pure water system (Aqualytic, Pretoria, South Africa). This system gives purity levels of elemental impurities, 18.2 MΩ-cm resistivity water and an extremely low TOC, typically <3 ppb.

All tests were performed using the AMPTS II from Bioprocess Control, Sweden. The methodology was exactly replicated (in triplicate) for the three waste composition variations provided in Table 3-2.

3.4. Data analysis method

Data analysis is a structured process of organising and categorizing data retrieved in a study. This application permits the researchers to understand and make logic out of large volumes of data retrieved in a study and to draw conclusions (Bengtsson, 2016).

The next sections provide an explanation of the data analysis of the laboratory results of the BMP tests of the ice cream only waste, as well as the three waste composition variations.

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[6] Collected from an existing industrial anaerobic digester in Bronkhorstspruit.

3.4.1. Data analysis of results of BMP tests of ice cream only

The data on the characteristics (moisture content, TS, VS and pH) of the ice cream only and quantity of methane gas produced during the BMP test was analysed through Microsoft Excel to determine the average and standard deviation (of the triplicate results). Biomethane output was normalised to Nml of CH_4/kg VS to allow for comparison of results.

Graphs were compiled to illustrate the Nml of CH4/kg VS produced over a 28-day period.

3.4.2. Data analysis of results of BMP test of waste composition variations (to determine optimal waste composition ratios)

The data on the characteristics (moisture content, TS, VS and pH) of the different waste variations; and quantity of methane gas produced during the BMP test by each of the three waste composition variations were analysed through Microsoft Excel. The assumption was made that, the larger the quantity of methane measured for the waste composition type, the higher the potential for biomethane production.

The average quantity of methane produced by each waste composition variation sample (methane potential) was calculated. Microsoft Excel was also used to calculate correlations between the physico-chemical characteristics and biomethane production potential, where a correlation coefficient of +1 indicates a perfect positive correlation (i.e. as variable X increases, variable Y increases; and as variable X decreases, variable Y decreases) and correlation coefficient of -1 indicates a perfect negative correlation. A correlation coefficient near 0 indicates no correlation.

Graphs were compiled to illustrate the Nml of CH4/kg VS produced by each of the waste variations over a 28-day period.

3.5. Ethical considerations

According to the North-West University (NWU, 2018), ethical considerations should be acknowledged and taken into consideration during research. The nature of this research does not include any animal or human participants. The research proposal for this study was reviewed by the Scientific Committee of the Environmental Management Research Group (EMRG) in the Unit for Environmental Sciences and Management and was exempted from full review by the Faculty of Natural and Agricultural Science's Research Ethics Committee (REC), because the methodology followed was considered to be a minimal ethical risk.

3.6. Methodological limitations

The main limitations of methodological in this study included locating a laboratory in South Africa that could conduct the BMP tests at reasonable cost. The location of the laboratory and the timing were also critical, as some laboratories were found but were already running tests and could not commit to a start date.

The cost of the laboratory testing was also extremely high, and some laboratories have stopped performing these tests due to the costs.

It was noted that very large quantities of waste volumes were also needed to conduct the tests and high-level approvals from Unilever needed to be granted to remove this waste off-site.

With regards to FOS/TAC measurement, after the samples had been digested, they were originally measured for FOS/TAC, however, the results did not consistently stay within the range that were measurable with the laboratory equipment and were therefore not reported as part of the results of this study.

3.7. Chapter summary

This chapter outlined the research design and methodology for this study, detailing the data collection and analysis, as well as the ethical considerations and limitations.

The next chapter (Chapter 4) will provide a detailed literature review to inform the research questions.

CHAPTER 4 LITERATURE REVIEW

4.1. Introduction

An overview of the negative impacts of LFG and potential advantages of biogas were provided in Section 1.1 and 1.2 of this dissertation, respectively, and will not be repeated here. This chapter will focus on the importance of WtE projects and provide an overview of the biogas (biomethane) production process, as well as the biogas to energy process to give an understanding of the factors involved.

The literature review aimed to identify historical data and research on biogas generation, and waste to energy plants to understand the optimum conditions for biogas generation through anaerobic digestion, with a specific focus on *waste composition*. The purpose was also to identify the key concepts of biogas production to use it as "lessons learned" for application by the ice cream factory in Midrand, South Africa.

The main aim of the literature review is to:

- Highlight the importance of waste to energy (WtE) projects in South Africa;
- Provide an overview of the *process* of biogas (and eventually biomethane) production during anaerobic digestion, with a specific focus on biogas from dairy-related waste;
- Understand whether dairy waste, more specifically ice cream waste, has the *potential to produce biomethane* and to understand the *optimum conditions* for the production of biomethane during anaerobic digestion; and
- Establish *global trends, success factors and challenges* of WtE projects, and more specifically anaerobic digestion, to inform the current study. Global trends in biogas production and management are discussed using the Europe, Asia and Africa as case examples, with specific mention of dairy WtE projects.

4.2. Importance of waste to energy (WtE) projects in South Africa

Waste to energy (WtE) projects, more specifically biogas to energy, may provide solutions to not only reduce the emissions from waste disposal (compared to the emissions from LFG) causing climate change, but also curb the energy deficit.

According to the United Nations Framework Convention on Climate Change (UNFCCC) (UN, 2011) the *Kyoto Protocol* is an international treaty that obliges countries to reduce greenhouse gas emissions thus reducing and eventually eliminating global warming. There are currently 192 parties that have signed this treaty, of which South Africa is one. There are three components to the protocol, firstly, emissions trading which is known as "the carbon market", secondly, the clean development mechanism (CDM) and lastly joint implementation (JI). South Africa has committed to the CDM component under Section 25 of the National Environmental Management Act (107 of 1998) (RSA, 1998) established by the Designated National Authority (DNA). Biogas-to-energy projects are examples of CDM projects that are being developed in South Africa in terms of the Kyoto Protocol.

In South Africa, the *National Development Plan* 2030 aims to create a better future for all citizens (National Planning Commission, 2012). One of the components is energy. The energy plan aims to create an energy sector that encourages economic growth and development through suitable investment in energy infrastructure. The plan also visualizes that by 2030 South Africa will have an acceptable supply of electricity and liquid fuels to ensure that economic activity and well-being are not disturbed and that at least 95% of the population will have admittance to grid or off-grid electricity.

The *White Paper on Renewable Energy* of 2003 (DME, 2003) is a policy that commits and details the South African government's plans relating to the development, demonstration and execution of renewable energy sources for both small and large-scale components. The policy highlights the need for cleaner and more advanced energy solutions as well as the heighten demand of energy in South Africa (DME, 2003).

South Africa generates large quantities of waste that is primarily disposed to landfill. The *National Waste Management Strategy* (DEA, 2011b) indicates that waste treatment and recovery (such as biogas to energy) is preferred instead of disposal at landfills.

The *National Climate Change Response White Paper* (DEA, 2011a) also highlights the fact that the waste sector, which includes biogas to energy projects, has the potential to mitigate GHGs.

The South African policy environment is favourable for the establishment of biogas to energy projects. The favourable policy environment, coupled with the current energy crisis that the country is facing, provide the motivation for the consideration of biogas-to-energy projects, as well as opportunities for these projects to perform well in the country.

As mentioned earlier, the South African presidency ratified the Kyoto Protocol that was approved on 11 December 1997 and was afterward established as a valid host country for the commissioning of CDM projects with the beginning of South Africa's DNA on 1 December 2004. Russia's signing of the Protocol on 16 February 2005 brought the commitments of the validation parties of Kyoto into full effect. The limited nature of CDM projects in South Africa and on the African continent under the UNFCCC's "*Waste Handling and Disposal*" portfolio is distressing, and the waste management industry should pursue the prospects offered by the expansion of

CDM projects. The Municipal Finance Management Act (MFMA) (RSA, 2003) and its related Supply Change Management Policy implemented by municipalities, provide strict legal constraints on the development of CDM projects and in specific the sale of carbon credits. It is noted that it would be beneficial for the expansion of CDM projects if there is an increase in demand pressure from a national level for the reinforcement of renewable energy and alternative energy initiatives (Strachan *et al.* 2008).

4.3. Biomethane from waste through anaerobic digestion

This section provides a brief overview on biomethane production from waste through the process of anaerobic digestion.

Anaerobic digestion is a microbial process where microorganisms break down larger, biodegradable molecules to simpler molecules, in the absence of oxygen. This process is achieved by microorganisms through a set of four interlinked metabolic steps, namely (1) hydrolysis[7], (2) acidogenesis[8], (3) acetogenesis[9] and (4) methanogenesis[10]. The main product formed during this process is biogas, which is a mixture of biomethane (CH_4), carbon dioxide (CO_2) and smaller quantities of other gases such as hydrogen sulphide (H_2S). A nutrient-rich slurry, known as digestate, is formed as a by-product (GreenCape, 2017).

The composition and quantity of the biogas produced depend on the composition and age of the waste, as well as other factors, discussed in Section 4.4 of this dissertation. Large variations may exist in the composition of biogas due to differences in sources of municipal solid waste and its characteristics (Staley & Barlaz, 2009). The next section explores the factors/conditions influencing biogas production.

4.4. Factors and conditions influencing biogas production

This section of the literature review, together with the laboratory analysis of the different waste composition variations, aims to provide context to the research question: "*Does the waste from the ice cream factory have the potential to produce biomethane?"* by specifically focusing on the factors and conditions influencing biogas production.

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[7] Hydrolysis involves the breakdown of carbohydrates, fats, and proteins, to sugars, fatty acids, and amino acids, respectively.

[8] Acidogenesis involves the development of carbonic acids and alcohols.

[9] Acetogenesis involves the development of acetic acid, carbon dioxide, and hydrogen.

[10] Methanogenesis is the development of methane.

Some of the main factors that affect the production of biogas include waste composition, moisture content, oxygen content, particle size, temperature, VFA and pH, C/N ratio, ammonia and metal elements, which will be discussed below.

Section 4.5 will provide a more detailed overview of how *waste composition* may influence biogas production and relates (together with the laboratory analysis of the different waste composition variations) to the research question: *"What is the optimal waste composition ratio that would produce the most quantity of biomethane?".*

Moisture content: Waste with a high moisture content supports bacterial decomposition. Waste with a higher moister content also increases the chances for chemical reactions that produce biogas (Le Hyaric *et al.*, 2011).

Oxygen content: Another factor affecting the production of biogas is oxygen content. Biogas is formed under oxygen deficient conditions by anaerobic bacteria. There is an inverse relationship between oxygen content and biogas production – the lesser the oxygen content, the more the biogas produced (Botheju & Bakke, 2011).

Particle size: According to Reinhart and Townsend (1998) smaller waste particle sizes are more favourable for biogas production than larger particles. Smaller particles will allow more of the waste surface area to be in contact with water and microorganisms, which increases the biological process that produces biogas.

Temperature: Temperature can affect the volume of biogas produced. Higher temperatures can rise bacterial decomposition, volatilisation and chemical reactions - all of which may increase the biogas production potential (Agency for Toxic Substances and Disease Registry, 2001).

VFA and pH: Volatile fatty acids (VFAs) which mostly contain acetic acid, propionic acid, butyric acid, and valeric acid, are the key transitional products during AD of organic wastes. Normally, VFAs produced in the anaerobic process could be eventually transformed into CH_4 and CO_2 by syntrophic acetogens and methanogenic bacteria. However, VFAs can be accrued at high organic loading, ensuing in the reduction of pH and even the failure of AD (Sluiter *et al.*, 2008a and Sluiter *et al.*, 2008b; Jiunn-Jyi *et al.*,1997).

C/N ratio: The performance of AD is knowingly affected by C/N ratio (Carbon/Nitrogen). An optimal C/N ratio is required for AD because a suitable nutrient balance is required by anaerobic bacteria for their growth as well as for sustaining the environment. Normally, a C/N ratio range of 20–30:1 was the optimal state for AD (Yan *et al.*, 2015).

Ammonia: Ammonia is shaped during the biodegradation process of protein or other nitrogen-rich organic substrates and mostly exists in the form of ammonium (NHþ4) and free ammonia (NH_3). It could be used as a vital nutrient for bacterial development however it can also be toxic to microbes in the occurrence of high concentrations. It is well known that ammonia plays a significant role in harmonizing the C/N ratio which could affect the output of AD greatly (Yenigün & Demirel, 2015).

Metal elements: Excluding the known nutrient elements (C, H, O, N), metal elements including light metals (Na, Kr, Mg, Ca, Al) and heavy metals (Cr, Co, Cu, Zn, Ni, etc.) may be present in organic wastes (contaminated by other wastes/substances). The composition of waste encompasses a vital role in the quantity and quality of biogas produced. These cations also play a vital element in enzyme synthesis as well as continuing enzyme activities. However, the production of biomethane may be inhibited by both of light and heavy metal elements when their concentrations are too elevated (Zhang *et al.,* 2014).

Type of biodigester: Biogas plants can employ mono-digesters, co-digesters, and latest technology tri-digesters, which influence the volume of gas output. Copious researches have determined that the performance of a two-phase anaerobic digestion system is more effective than a single-phase one. However, in a single-phase anaerobic digestion system, all reactions (hydrolysis, acidification and methanogenesis) happen simultaneously in a single reactor, which permits for a simpler design (Nagao *et al.,* 2012). It has been stated that in Europe, 95% of anaerobic reactors for organic wastes are single-phase anaerobic digestion systems. The newest anaerobic digestion systems and technologies involve a compact three-stage anaerobic digester, which is suitable for food waste digestion. Three independent chambers are joined for hydrolysis, acidification, and methanogenesis. High methane yields are attained. Studies have shown an increase of biogas production by 24% to 54%, compared to single-phase or two-phase anaerobic digestion systems (Forster-Carneiro *et al.,* 2008).

According to Nagao *et al.* (2012), the high biodegradability of food waste makes it a suitable organic substrate for AD. However, mono-digestion of food waste often digests unpredictably, and failure may occur at higher organic loading rates, particularly under thermophilic circumstances, due to the accumulation of VFAs and ammonia, as mentioned earlier.

Co-digestion and addition of substrates: Co-digestion of food waste with manure, sewage sludge, and lignocellulosic biomass could be valuable due to dilution of toxic chemicals, improved balance of nutrients, and synergistic effect of microorganisms (Demirel *et al.,* 2013).

The co-substrates can supply micro-nutrients and alkalinity, overcome the disadvantages in single digestion of food waste, more proficiently use equipment, and segment costs by processing multiple waste streams in a single facility. Thus, co-digestion seems capable of improving digestion efficiencies and process performance. Co-digestion of manure and food waste can increase the maximum acceptable organic loading rate (OLR), deliver a more stable environment for anaerobic microbes, and increase the biodegradation of high-carbon substrates such as lipids (Demirel *et al.,* 2013). Sewage sludge is an extensively studied co-substrate for food waste due to its high alkalinity and trace elements content (Kim *et al.,* 2007). Sewage sludge also encompasses large quantities of active microorganisms, which are valuable for the progress of diverse groups of microbes involved in the AD process (Razaviarani *et al.*, 2013). The optional mixing ratio of food waste and sewage sludge differs across the literature (Kim *et al.,* 2003).

Based on the factors (mentioned above), which may have an effect on biogas/biomethane production, it is clear that the composition of waste (and its physico-chemical characteristics) play(s) an important role in the quantity and quality of biogas produced. The next section focuses on how waste composition may influence biogas production, which is one of the main objectives of this study.

4.5. Waste composition and biogas production

Waste composition affects the formation of biogas. The higher the organic waste composition, the more bacterial decomposition occurs and the more biogas (and eventually biomethane) is produced (Agency for Toxic Substances and Disease Registry, 2001). Previous researchers demonstrated that methane yields from food waste vary due to the various compositions of substrates (also refer to the aspects mentioned in Section 4.4) (Zen *et al.,* 2010).

According to Zhang *et al.* (2014), anaerobic digestion is a reliable technology for harnessing bioenergy from food waste. Food waste could be processed successfully under both mesophilic[11] and thermophilic[12] conditions. Other than temperature playing a role, researchers have determined that the composition of food waste (and substrates available for bio digestion) are also important in influencing the amount of biogas formed. Zhang *et al.* (2014) have determined that a buffer system, moulded by VFAs and ammonia, resulted in higher methane yields and improved system stability, compared to food waste only. The additional trace elements added to food waste provided a favourable environment for the anaerobic digestion of food waste, since the trace essentials (for biodigestion) in food waste may be insufficient. The concentration of lipids in food waste is generally high, consequentially leading to the inhibition of anaerobic digestion.

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[11] Mesophilic: Moderate temperatures, neither too hot nor too cold, typically between 20 and 45 °C.

[12] Thermophilic: Relatively high temperatures, between 41 and 122 °C.

However, lipids are high potential bio-resources for methane production. Co-digestion of food waste with other substrates such as cattle manure (which contains ammonia) could improve the biodegradation of long chain fatty acids, which in turn increases the methane yield.

According to Rodrigo *et al.* (2011) the biomethane potential and biodegradability of a range of substrates with exceedingly heterogeneous characteristics, including single and co-digestion samples with dairy manure, were determined using the biochemical methane potential assay. In addition, the aptitude of two theoretical methods to approximate the biomethane potential of substrates and the effect of biodegradability was assessed. The results of about 175 individual BMP assays indicated that substrates rich in lipids and easily degradable carbohydrates yielded the maximum methane production potential, while more stubborn substrates with a high lignocellulosic fraction (such as plant matter and fruit) had the lowest methane production potential. In their study, co-digestion of dairy manure with easily degradable substrates increased the specific methane yields when compared to manure-only digestion. Furthermore, biomethane potential of some co-digestion mixtures suggested synergistic activity (Rodrigo *et al.*, 2011).

Lisboa and Lansing (2013) assessed the potential for biogas production from a range of food waste substrates, such as meatball, chicken, cranberry, and ice cream processing wastes. Their study concluded that the co-digestion of certain wastes may increase the amount of biogas being produced (compared to the wastes being digested individually). They have also found that ice cream waste mixed with manure (for instance) showed a 67% increase in the production of biogas, compared to digesting ice cream waste alone. Ninga *et al.* (2012) also determined a higher methane yield for mixed food waste, as compared to certain types of food being digested individually.

Demirel *et al.* (2013) did research to determine and quantify the possibility to recover energy (biogas) from ice-cream production residues and wastewater, through a mesophilic anaerobic co-digestion process. Relatively high methane outputs of approximately 0.338 litres of CH_4 per gram of COD removed could be attained from anaerobic digestion of ice-cream wastewater alone, with nearly 70% biomethane measured in the biogas produced. The same study determined that biomethane production from anaerobic digestion of the ice-cream residue only did not seem feasible.

In conclusion, the studies revealed that mixed food wastes were generally more favourable for the generation of biomethane, than certain food wastes on its own. The reason mainly being that the co-digestion of certain food wastes provides elements, which could assist in breaking down and digesting fatty acids, which would otherwise (in the absence of the mixed waste) be difficult to break down and may inhibit biomethane production. The experimental design (as explained in

Section 3.3 of this dissertation), therefore, provided for different waste composition variations to determine the optimal composition for the production of biomethane from waste generated by the Unilever ice cream factory.

4.6. Dairy industry projects on biogas production

According to Lhanafi *et al.* (2017) the composition of sludge from the dairy industry is appropriate for the production of biomethane, since it consists between 74% and 95% or organic matter. The key biodegradable portions of dairy waste are lactic acid, lactose (so-called “lactic sugar”), fat and casein (Pilarska *et al.,* 2013). However, with their pH in the acidic range, low content of total solids and low C/N ratio, dairy-related wastes need a sufficient number of co-substrates to enhance methane production (as also mentioned in Section 4.5).

Additionally, it is known that the cause of less biogas and less methane being formed from cheese whey, for example, is fundamentally due to its lower TS value and low content of fat and protein (a total of 1.5% or less) (WSP, 2009). Fat and protein are sources of H_2 which, in reactions with CO_2, is vital to produce CH_4 (WSP, 2009). Therefore, substrates with a higher fat and protein value, may produce larger quantities of biomethane. However, they may be more difficult to biodigest (as explained in Section 4.5), which may necessitate the addition of co-substrates.

According to Macias-Corral *et al.* (2008), anaerobic digestion of dairy cow manure (CM), the organic fraction of municipal solid waste (OFMSW) and cotton gin waste (CGW) was investigated with a two-phase pilot-scale anaerobic digestion system. The OFMSW and CM were digested as single wastes and as joint (mixed) wastes. The single waste digestion of CM resulted in 62 m^3 of methane being produced per tonne of CM on dry weight basis. The single waste digestion of OFMSW produced 37 m^3 methane per tonne of dry waste. While, co-digestion of OFMSW and CM (as a mixed substrate) resulted in 172 m^3 methane per tonne of dry waste, and co-digestion of CGW and CM formed 87 m^3 methane per tonne of dry waste. From the results it is clear that co-digestion resulted in higher methane gas yields than single substrate waste digestions. Furthermore, co-digestion of OFMSW and CM encouraged synergistic effects resulting in higher mass conversion, and lower weight and volume of digested residual.

An analysis of studies specifically focusing on WtE of the dairy industry also revealed that the co-processing of waste substrates may be more favourable for the formation of biomethane than single substrate wastes.

4.7. International examples: Success factors and challenges of WtE (biogas to energy) projects

The third research question related to understanding "What *supporting elements* are necessary for the successful implementation of WtE projects?" The supporting elements, in this context, refer to important aspects that need to be in place, other than the physico-chemical composition of waste, which would enhance the successful implementation of WtE projects. These may include a supporting policy or legislative environment (as explained in Section 4.2), specific technologies, funding, etc.

Lessons learned, from global examples, as far as WtE, more specifically biogas to energy, projects are important to inform the optimal conditions for the formation of biogas. The aim of this section of the literature review chapter is to use the lessons learned and best practices from other countries, to inform the supporting/enabling environment context, which may enhance the successful implementation of WtE projects.

4.7.1. Europe

There are many success stories of biogas from anaerobic digestion projects in Europe. The next few sections will discuss some of the challenges and success factors in some European countries.

4.7.1.1. Austria

Vienna's waste management system is comprised of recycling, aerobic and anaerobic composting, three grate combustion WtE plants and an RDF fluidized bed incinerator. It is estimated that approximately 0.63 tonnes of waste are generated per capita, of which 23% is recycled, 11% composted, 63% combusted and less than 3% landfilled. Vienna generates 25% of its regional heating from its WtE plants. Overall, it combusts 667,000 tonnes of MSW and generates 0.16 MWh of electricity per year, plus 1.73 MWh of heat per tonne of waste combusted, conforming to 75% thermal efficiency (Psomopoulos *et al.,* 2013). The success of Vienna's WtE projects lies in the fact that the government has invested financial capital and knowledge to develop and implement WtE projects, which are suitable to the city's waste composition profile, which also has the optimal temperature and moisture content. The support of the government with funding and knowledge sharing with regards to WtE were the main element to a successful WtE commissioning in Vienna (Psomopoulos *et al.,* 2013).

4.7.1.2. Switzerland

According to Pelkmans (2018), historically, Switzerland's lengthiest and most significant source of renewable energy has been hydropower. But the newer renewables, like bioenergy, are starting to play an increasingly vital role in the present-day Swiss energy mix. Biomass is the second most important domestic source of renewable energy. Comparably, however, biomass provides 5.5% of the total energy consumed in Switzerland, while its portion in electricity production is approximately 2.9%. With regard to renewable heat, 68% is from biomass of which 52% comes from solely wood combustion. It is projected that 10% of the final Swiss energy consumption could be enclosed with domestic biomass sources and this in an environmentally suitable means. To what degree this probably can be exploited relies on specifics on developments in technology and energy efficiency, the price of raw materials and prices for bioenergy on the domestic and international markets, and not least on political measures to boost use of biomass and social acceptance of the technology (Pelkmans, 2018).

Biogas and biomethane production in Switzerland are attained in 423 biogas plants and three landfills. With 275 (64%) plants, domestic sewage sludge digesters outnumber all other categories of AD plants. With 27 plants, biowaste AD commissioning is relatively small, but considered by installations with a high average treatment capacity of 18’000 t/year. Associated to this, the 98 agricultural AD installations, mostly co-digesting manure and organic wastes, show an average treatment capacity of about 7,600 t/year. Industrial wastewater digesters are few with only 23 installations mostly located in the food and beverage industry. The total gross biogas production in Switzerland was 1350 GWh in 2016. Roughly, 44% thereof is produced in WWTP sludge digesters whereas agricultural co-digestion and industrial biowaste digestion accounts for 25% each (Pelkmans, 2018).

The lessons learnt from this country is the proper planning and governmental controls in getting the best for WtE plants for the countries use. Switzerland used well-known companies like Hitachi to establish the WtE plants as they have the skill set to commission these plants and transferred the knowledge to locals for continual maintenance. An important factor is the government’s willingness to investment in WtE plants with legal backing of the energy policies and financial resources for maintenance.

4.7.1.3. Netherlands

In the Netherlands, the capital of Amsterdam has two waste-to-energy plants on the same site. Approximately 1.4 million tonnes of waste are annually incinerated and converted to energy. The waste-fired power plant (WFPP) built in 2007 has a heat rate (heat-to-electricity efficiency) of 30%, which is the greatest in the globe for waste-to energy plants. The installation has produced 580,000 MWh of electrical energy, 102,000 GJ of heat and 180,000 tonnes of building materials from bottom ash (reduces air pollution and with an optimistic reaction from the residents) (Psomopoulos *et al.,* 2013).

As part of the cleaner efficiency program, the Dutch dairy chain is targeting energy-neutral production (Gebrezgabher *et al.*, 2010). This new initiative is titled the *Energy-Neutral Milk Initiative* and its goal is to incorporate the entire supply chain, i.e. from the dairy farm to the factory and eventually to be self-sufficient in energy in 2020. This is foreseen to be achieved by building fermentation units to convert manure and food waste into biogas, which can then be utilized (directly or indirectly) by local dairy factories.

WtE options in Europe are well-designed, equipped and benefits the country and its people. They require planned maintenance but can last over three decades. WtE operations do not need more land than the initial requirement, unless they are extended to process more MSW. An example is, with landscaping and supplementary buildings, a WtE facility processing 1 million tonnes of waste per year needing less than 100,000 m^2 of land (Psomopoulos *et al.* 2013).

In conclusion, European cities use energy recovery from wastes and considers this as a key parameter of these achievements. Wastes are an appreciated source of materials and renewable energy. Waste incineration delivers electricity, heat, financial growth, employment and solves the dilemma of treatment of the non-recyclable part of MSW.

4.7.2. Asia

In Asia, waste (biogas) to energy projects are implemented to some extent, however, historically, there was limited resources to build and maintain this technology (Yedla & Parikh, 2001). In the next few sections a few counties in Asia will be discussed relating to WtE projects.

4.7.2.1. India

Development of biogas digesters begun in India in 1939, with the initial plants constructed on a mass scale for distribution in 1960 by the Khadi Village (Bhat *et al.,* 2001). The National Programme on Biogas Development (NPBD) was executed in 1982 with the purpose that biogas could supply all the cooking energy needs for rural households. Presently, it is known as one of the largest biogas programmes in the world. Despite this fete, highly competitive distribution led to unhealthy rivalry between the construction companies, thus resulting in reduced standards of construction and materials, suitability and sustainability standards being disregarded, contradictions in the reporting of attainments, and a lack of follow up services and responsibility for maintenance. To discourse these issues, the government combined NPBD with the manure management initiative in 2005 to develop the National Biogas and Manure Management Programme (NBMMP).

There were also other issues which include, partial awareness and education for biogas users on how to boost the benefits from their system, deficiency of training and follow-up services, mainly for female biogas users, and high installation costs, and/or inadequate supply of cow dung (Raha *et al.*, 2014; Patankar *et al.*, 2010).

4.7.2.2. Malaysia

In Malaysia, energy recovery enterprises are focused on application of waste-to-energy (WtE) as well as refuse-derived fuel (RDF) technologies (Abd Kadir *et al.*, 2013). Biodigesters are used with the main feed being animal waste. With the increased volume of animal husbandries opening, there is an increased correlating volume of animal waste including manure, blood and rumen. These types of animal waste contents have great biogas production potential. The study by Abdeshahian *et al.* (2016), details how the animal waste from farms and slaughterhouses in Malaysia, have used these waste types to harness the methane into energy. This study proved that animal waste is the most capable low-cost and sustainable energy source in Malaysia, which could be proficiently utilized for the generation of biogas energy. Additionally, anaerobic digestion of animal waste decreases their harmful impacts on the environment by promoting public health rather than dumping in landfill which releases uncontrolled methane into the atmosphere. The lessons learnt is evident that organic matter makes one of the best by-products to produce biogas.

The issues, similar to other developing countries, is that of the technical and fiscal viabilities of future waste-to-energy incineration systems retains extremely substantial as renewable energy generation in Malaysia fastens pace. It is vital that planned incineration plants be properly managed by an efficient organization and with effective budget allocation and monitoring.

4.7.2.3. Indonesia

The Hitachi Zosen's feasibility study of a large-scale incineration plant has been applied in Indonesia. Hitachi Zosen is a global leader in the development and operation of thermal conversion WtE facilities. The corporation has commissioned nearly 200 incinerators in Japan and presently operate approximately 50 plants. Its development plans comprise of many countries, including Indonesia. In 2012, Hitachi commenced a comprehensive assessment of building an MSW incinerator in Indonesia (Hitachi Zosen, 2012). Financial modelling was performed by Hitachi to understand the viability of commissioning a WtE plant. However, Hitachi's feasibility study did not deliberate Indonesia's current and future MSW projects. As a consequence, the project was considered uneconomical, so the corporation provisionally postponed its projects in Indonesia's WtE division.

4.7.2.4. China

China is the main biogas producer and user in the world with between 30 and 40 million domestic scale biogas plants commissioned all over the country. Since 1986, the government has been introducing and executing energy policies that back the development and amplified use of renewable energy, including biogas. In 2012, the country already had 40,000 full-time employees working in 8000 rural energy offices in over 1900 regions and towns to supervise the administration of biogas in rural areas with education, support and training provided by the Ministry of Agriculture (Chen *et al.*, 2012).

According to Kranert *et al.*, (2012) the biogas sector in China saw a rapid rise from the early 2000s up to 2010, owing to the government providing provision for the construction of rural household digesters, as well as some medium and large-scale systems, known as the National Debt Project for Rural Biogas Construction. Despite the scale and success of biogas systems in China, they have faced and are still enduring some challenges, which include systems being underutilised or abandoned due to movement of rural labour to the cities, popularity of commercial energy use, decay in backyard farming and unbalanced supply of feedstock due to variations in livestock breeding, technical difficulties due to defective or low quality materials and inadequate product support, deficiency of training and follow-up for farmers with household systems. This had led to meagre operation and maintenance and weak demand as the combined benefits, mainly direct economic benefits, have not been achieved. Various household digesters commissioned prior to the 1990s, failed, as many of these systems were unheated and led to low or unbalanced biogas production, especially in Northern China, where the average temperature is between 10 ºC and 15 ºC for most of the year. This issue is improbable in the majority of the parts of South Asia (and Africa) due to the warmer climate (Jiang *et al.*, 2011).

4.7.2.5. Nepal

According to Gurung (2013), the energy supply condition in Nepal can be compared to that in many Asian countries. Fuelwood, agricultural residues and animal waste are the main energy resources in the country due to a low electrification rate, limited fossil fuel resources which leads to a reliance on expensive fuel imports. Nepal has successfully commissioned 260,899 biogas systems which was dated in 2012.

Nepal's biogas success has been credited to seven main factors which include, intensifying level of awareness of the assistance among the rural population; energy, health and environmental costs related with traditional energy sources; unreachable and underdeveloped rural communities with minimal or no modern fuel supplies; plentiful organic waste supplies on farms for use in biogas systems; technology accessible freely, without intellectual property rights issues; rapidly available raw construction materials; and the obtainability of loans and subsidies from the government (Gurung, 2013).

The main issues facing the biogas sector in Nepal are cold temperatures in many of the country's mountainous areas, making conventional biogas systems impracticable; need for better private sector capability for biogas system installations; remote locations of many villages, making application of the systems problematic; the technology still being too costly for some rural households which are omitted from government subsidies; lack of acceptable water supplies to operate biogas plants in mountainous regions; and amplified mosquito prevalence reported by biogas system users after installation, also producing opposing publicity of the technology. However, biogas technology has also added to increasing the socio-economic status of its users in Nepal (Gautam *et al.*, 2009; Khanal *et al.*, 2011).

According to Katuwal and Bohara (2009), the best-known recorded benefits are the decrease in the workload and time spent on household activities, with women as the main recipients improved health for families due to decreased indoor smoke and air pollution from their location or reduction of firewood and dun cake use, particularly for cooking; enhanced sanitation levels through linking a toilet to the system; enlarged productivity in crops and kitchen gardens; substituted use of raw dung and chemical fertilisers on crops and employment.

4.7.3. Africa

In Africa, similarly to Asia, there is a lot of potential for WtE projects, however, the concern is funding and skills to develop and maintain these facilities (Strachan *et al.* 2008). WtE projects within the African continent has experienced and is still facing the discouraging trials of coal reserves, which is the most known source of energy and low oil reserves reaching high and unstable prices. Some African countries have started moving towards implementing and utilizing renewable energy sources, therefore declaring the green energy revolution agenda in the continent. A few African countries have recognized WtE projects, although on varying scales on success and implementation (Strachan *et al.* 2008).

4.7.3.1. Kenya

According to Roopnarain and Adeleke (2017) a sudden rising in the biogas sector in Kenya begun in 2010 with the development of the Kenyan National Domestic Biogas Programme (KENDBIP). The KENDBIP was started by the African Biogas Partnership Programme (ABPP). The achievement of the programme in Kenya was emphasized by the construction of 10,000 biogas digesters by September 2013, which had positively impacted the lives of approximately 50,000

Kenyans. Despite the success of this project, there were also challenges faced, including the acceptance and long-term process of biogas technology and its' high investment input for the construction of the digester system. Another hurdle was feedstock availability and lack of communication which relates to the technology aspect and the ready availability of cow dung in large and sufficient quantities to sustain the production of suitable amounts of biogas for large African families.

4.7.3.2. Nigeria

According to Ituen *et al.* (2009), in sight of the necessity for environmental management, waste recycling and alternative energy resources, since 2009, there has been on-going work on biogas production with a locally fabricated digester in Akwa Ibom State of Nigeria. The first result demonstrated that 0.032 m^3 of biogas was formed from 180 litres of poultry manure mixed with same volume of moisture in sixteen days. Using the same concentration of cow dung in a recurrence experiment, 0.015 m^3 of biogas was produced in seven days. There was disruption in the gas production in the second case due to excessive wetness of weather. Supplementary studies indicated that the volume of gas changed, and it was dependant on the ambient temperature as seen in the second experiment. A maximum volume of 0.006 m^3 was received for the maximum temperature 51 °C and a minimum volume of 0.00 m^3 got for the minimum temperature of 22 °C. They also detected that the gas yield with poultry manure was higher than that with cow dung.

The low adoption rate of biogas technology in Nigeria, similar to the rest of Africa, is mainly due to the deficiency of government incentives, governmental commitment, eagerness and support (which is critical for the promotion of renewable energy efforts) by both foreign and private sector investors.

4.7.3.3. South Africa

In South Africa, 700 digesters were installed since the introduction of the biogas technology in the country in 1957 (Mutungwazi *et al.,* 2018). The initial biogas digester in South Africa was installed in 1957 by John Fry which was located on a pig farm and the waste input utilized was pig manure. In 1958, electricity was generated from the formed biogas to power pumps on the farm. Since then, South Africa has practiced partial market penetration for biogas. The explanation for this restriction include the low-priced cost electricity from other sources such as fossil fuels, inadequate grants or government incentives to support the biogas technology and inaccessibility of local biogas technology providers. However, there has been some successful projects like the Cape Flats biogas digester for dewatering sludge in 2003. Also, in 2003, the commissioning of a

1 MW digester was commenced in Marianhill in Durban and was finalized in 2010 (a model adopted from Germany and funded by the eThekweni local government). In 2009, Mark Tiepelt created BiogasSA after numerous unsuccessful attempts to locate a local company that could install a biogas digester in Johannesburg, therefore this was a privately funded biogas project (Mutungwazi *et al.,* 2018).

Africa green energy technologies (AGET), a private company in Cape Town, has created a 10 m^3 underground digester which consumes a daily substrate input volume of 120 kg to produce 8 m^3 of biogas which can output approximately 8 kWh of energy. The digester functions together with a separate biobag which accepts biogas collected from a digester. The positives of this design include the biobag which is lightweight, safe, and environmentally friendly and connects to several required appliances (e.g. stove, lamp and heaters). This digester has the benefit over other underground digesters of a portable gas storage bag (biobag) which can be stored anywhere and pumped at the suitable pressure through use of a gas pump (Munganga, 2013).

The Agama fixed dome digester was created in South Africa by BiogasPro and its clients include farmers, rural schools, eco-lodges, and "green" households which are mainly rural. This digester is a plastic rotary mould digester which the functioning principle of the traditional fixed dome digester. This 6m^3 volume digester consumes 40 kg of mixed organic raw material per day and is able of producing a maximum of 2 m^3 of biogas per day, which is comparable to 3.5 kWh of continuous electrical output which is equivalent to 4 hours burning time (Bhattacherjee, 2013).

According to Hamilton (2014) a complete mix digester is essentially a tank in which substrate is heated and mixed with an active form of anaerobic microorganisms. This digester design is a high rate system. An example is the up-flow anaerobic sludge blanket digester. The disadvantages of this system include the elevated capital and energy costs, loss of anaerobic microorganisms from the digester and the necessity for maintenance of the mechanical parts of the digester intermittently. The most well-known use of the complete mix digesters in South Africa is in abattoirs, food processing plants and fruit and vegetable packaging.

The history of biogas digesters in South Africa has been charted and the list of the installed biogas digesters under different scales given. It has been revealed that the biogas digester design standards to be considered in the variety of a suitable digester design are strength, airtightness, availability of construction materials in the zone, rate of construction, ease of operation, simplicity and cost of maintenance, efficiency, feasibility of insulation and reliability and temperature conditions. (Mutungwazi *et al.,* 2018).

As mentioned in section 4.2, in South Africa, there is a legal framework that guide and support the implementation of WtE technologies. The policy framework provided by the National Development Plan 2030, the White Paper on Renewable Energy of 2003 (DME, 2003), the National Waste Management Strategy (DEA, 2011b), as well as the National Climate Change Response White Paper (DEA, 2011a) provides a policy environment which is favourable for the establishment of biogas to energy projects.

According to the Department of Science and Technology (DST, 2014), there is progress with regards to AD plants and general waste management in South Africa. This is due to new targets and policies as well as funding strategies. The latest 2025 target is 20% reduction (by weight) in industrial waste and a 60% reduction (by weight) in domestic waste to landfill. The goal is to increase recycling and find alternative waste management practises like AD plants. The funding strategy is various from private to industrial to government funding as well co-funding between industry and government. The favourable policy environment, coupled with the current energy crisis that the country is facing, provide the motivation for the consideration of biogas-to-energy projects, as well as opportunities for these projects to perform well in the country (Strachan *et al.* 2008).

4.7.4. Summary of lessons learned from WtE projects

Section 4.7 aimed to provide information and lessons learned from other countries, as it relates to the research question: *What are the optimal conditions that would produce the most quantity of biomethane?*

According to the best practices and lessons learned from other countries, the following main aspects are deemed to be applicable to this study:

- Government support is critical especially in areas whereby environmental laws are pertinent. Government support are required by many countries struggling to commission WtE plants due to strict laws on energy and waste management and contradicting environmental policies

- Sufficient research is required to implement a successful WtE plant. As learnt through the Hitachi Zosen (2012) experience in Indonesia, the implementation of research findings are critical.

- Proper planning is important, from the conception of the project to the construction and maintenance. Planning and skills transferred from training is critical. In many developing countries, there is not much exposure and many expertise to WtE industry as they are mainly focused on landfill management. If an international company commissions a WtE plant in a country, they need to plan and share the skills of the running and maintenance of this plant to ensure a safe and sustainable WtE project

- Capital is required to approve the plans as well as construct and maintain the plant for future years. This is a critical element from design to commissioning to maintenance. Sufficient budgeting and planning need to be in place to ensure the project does not run out of capital throughout the lifespan of the facility
- Sufficient and continuous organic waste is required and knowledge of the ratio of waste required to produce energy. This forms part of the research and planning portion as it covers what waste mix is available for the location
- The digester should be designed according to the local requirements (output required, source available and weather conditions). This is critical as this forms part of the volume and production of gas and the most sustainable way of use for the location to ensure the design is not over or under specified

4.8. Chapter Summary

This chapter discusses the trends in the waste to energy industry specifically diary waste to methane production. Many lessons learnt were discussed from international to national examples and what the process and output compromises of. The next sessions will discuss the results of the study.

CHAPTER 5 RESULTS AND DISCUSSION

5.1. Introduction

This chapter provides the results and discussion of the study, which relate to the three research questions:

1. Does waste from the ice cream factory have the *potential to produce biomethane during anaerobic digestion*? (RQ1)
2. What is the *optimal waste composition ratio/profile* that would produce the most (quantity) biomethane during anaerobic digestion? (RQ2)
3. What *supporting elements* are necessary for the successful implementation of WtE projects? (RQ3)

In summary, ice cream waste and three different waste mixtures (variations), all containing ice cream waste plus other related wastes from the ice cream manufacturing process (refer to Table 3-2) were tested (in triplicate) for its potential to produce biomethane. The results indicated that there is potential biomethane production from ice cream, which is comparable to literature. The optimal waste mix for the production of the most (quantity) biomethane was ice cream waste mixed with ice cream sludge, based on a ratio of 60:40 (ice cream: ice cream sludge). It is known from the study by Lhanafi *et al.* (2017) that the most known way to increase the output of biomethane production is to ensure the dairy waste is mixed with a substrate, for example dairy sludge. The results of the study, as it relates to the three research questions, are discussed in Sections 5.2 to 5.4.

5.2. Results and discussion on RQ1: Potential of ice cream waste to produce biomethane

According to Lhanafi *et al.* (2017), the composition of dairy product-related sludge from the dairy industry is appropriate for the production of biomethane, since it consists of between 74% and 95% of organic matter. The key biodegradable portions of dairy waste are lactic acid, lactose (so-called “lactic sugar”), fat and casein (Pilarska *et al.,* 2013). However, with their pH in the acidic range, low content of total solids and low C/N ratio, dairy-related wastes need a sufficient number of co-substrates to enhance methane production (as also mentioned in Section 4.5 and 4.6).

The objective of the first research question (RQ1) was to understand whether ice cream waste (when not mixed with any co-substrates) has the *potential* to produce biomethane during anaerobic digestion. To answer this question, the moisture content, TS, VS and pH and biomethane output of ice cream waste were determined (as explained in Chapter 3).

As mentioned in the literature review chapter, waste with a high moisture content supports bacterial decomposition. Waste with a higher moisture content also increases the chances for chemical reactions that produce biogas. Therefore, wastes with a higher moisture content may give rise to higher production of biogas (Lay *et al.*, 1997).

TS and VS are important parameters, when determining biomethane production potential, since they can assist in determining the characteristics of the substrate (in this case ice cream-related waste). TS are used to determine the loading rate that the anaerobic digester may have and may give information on when maintenance is needed. In anaerobic digestion substrates, focusing on food waste as a substrate, TS normally amount to up to 10% of the total volume (Parawira *et al.*, 2004). The VS content may give an indication of the amount of substrate that can potentially be converted into biomethane. It only provides an estimate, since VS are made up of different organic compounds with variable degradability speeds (El-Mashad *et al.*, 2004). Varying results are reported in literature on TS/VS ratio and its correlation with biomethane production. Some authors have found that the lowest ratio corresponds to the lowest production of methane (Hill & Bolte, 2000), while others have found that a lower ratio may correspond to higher methane production (Oleszkiewicz & Poggi-Varaldo, 1997).

According to research done by Wong *et al.* (2013), an alkaline pH (8 – 10) may be beneficial for biomethane production during the anaerobic digestion process. The authors found that pre-treatment of waste activated sludge, to a pH of 10, enhanced biomethane production, with a maximum methane yield of approximately 4-fold higher than waste sludge with an acidic pH (which was not pre-treated).

Although these publications on the characteristics of substrates used in anaerobic digestion provide interesting insight into the production of biomethane, the main aim of this study *was not* to make any in-depth correlations between the characteristics of the ice cream-related waste and the amount of biomethane production. The research rather focused on determining the potential of ice cream-related wastes to produce biomethane and to determine the optimal waste composition profile. The characteristics of the samples are therefore only reported in the context of the research questions and to compare the characteristics of the samples used in this study to what others have found during similar studies. Results of the characteristics of ice cream only are presented in Table 5-1, while the biomethane production is reported in Table 5-2.

Table 5-1: **Characteristics (TS, VS and pH) of ice cream waste only as compared to the characteristics of dairy and ice cream waste reported in literature (Xu *et al.*, 2018, Lisboa & Lansing, 2013 and Demirel *et al.*, 2004)**

Parameter	Characteristics of ice cream waste only (present study)	Characteristics of dairy waste (Xu *et al.*, 2018)	Characteristics of ice cream (Lisboa & Lansing, 2013)	Characteristics of ice cream production residue (Demirel *et al.*, 2004)
Moisture content (%)	79.48	-	-	-
Total solids (TS) (% of sample)	20.52	0.1 – 7	8.7 – 9.5	16 – 25
[13]Volatile solids (VS) (% of TS)	85.39	-	88 - 98	89 – 93
pH	8.66	6 - 11	4.39	3.47 – 4.28

The characteristics of the ice cream waste determined during this study compared well with what was found by others (Table 5-1). The TS and VS values were within the range of Demirel's findings. The pH of the ice cream (only) waste was, however relatively higher (more alkaline) than that measured by Lisboa & Lansing (2013) for ice cream and by Demirel *et al.*, (2004) for ice cream production residue, but within the range reported by Xu *et al.* (2018) for dairy waste.

The biomethane output of the ice cream waste (only) sample is provided in Table 5-2. The baseline value provided in the table represents the biomethane yield produced by the inoculum (as a baseline) without the addition of the ice cream waste.

Table 5-2: **Biomethane output (in Nml CH_4/kgVS) from ice cream waste (only) measured in triplicate. The baseline value represents the biomethane output produced by the inoculum.**

Waste stream	Biomethane output (Cumulative methane production) Nml			Standard deviation	Average biomethane output
	Test 1	Test 2	Test 3		
Baseline	190.2	205.4	183.10	11.39	192.9 ± 11.39
Ice cream waste only	1890	1997.3	1795.4	101.02	1894.2 ± 101.02

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[13] Volatile solids are expressed as a percentage of total solids.

It should be noted that ice cream waste has the potential to produce biomethane and that it is generally high when compared to other dairy (and ice cream) studies. Derimel *et al.* (2004) have reported cumulative methane yields of approximately 380 ml for ice cream production residue. When the ice cream residue was mixed with ice cream waste water at a ratio of 3:1 (waste water: ice cream), cumulative biomethane production reduced to 145 ml of biomethane. However, at ratios of 6:1 and 9:1 (waste water: ice cream), the cumulative biomethane yield increased to 635 ml and 1838 ml, respectively. Thus, biomethane production is generally higher when the ice cream waste is mixed with a suitable substrate (refer to results of Derimel *et al.*, 2004).

5.3. Results and discussion on RQ2: Most optimal ice cream waste mixture (variation) to produce the most (quantity) biomethane

It is known (from various studies done on the anaerobic digestion of dairy wastes) that substrates with a higher fat and protein value, may produce larger quantities of biomethane. However, they may be more difficult to biodigest (as explained in Section 4.5), which may necessitate the addition of co-substrates (such as sludges or waste water). The second research question, therefore, focused on determining the optimal *waste composition ratio/profile* that would produce the most (quantity) biomethane. The waste composition variations tested were based on the waste streams that are generally produced by the Ola ice cream factory, as explained in Section 3.3 of this dissertation.

Section 5.3.1 (Table 5-3) provides the results on the characteristics (moisture content, TS, VS and pH) of the different ice cream waste variations. Section 5.3.2 reports on the biomethane yield (output) of the different waste mixtures (Table 5-4 and Figure 5-1), with more detail on the biomethane output of each of the waste variations over a 28-day period provided in Figures 5-2 to 5-6. Finally, Section 5.3.3 (Table 5-5) attempts to draw correlations between biomethane production and the physico-chemical characteristics of the waste variations (mixtures).

5.3.1. Characteristics of the different waste variations (mixtures)

Table 5-3 provides the characteristics (moisture content, TS, VS and pH) of the four different waste variations analysed during this study.

Table 5-3: Characteristics (moisture content, TS, VS and pH) of ice cream waste only as well as the characteristics of the three other waste composition variations

Parameter	Characteristics of ice cream waste only	Waste variation 1 (60% Ice Cream, 40% ice cream sludge)	Waste variation 2 (60% ice cream, 20% sludge, 20% wood chips)	Waste variation 3 (60% ice cream, 20% raw material, 20% wood chips)
Moisture content (%)	79.48	89.27	10.94	7.07
Total solids (TS) (% of sample)	20.52	10.73	92.93	89.06
Volatile solids (VS) (as a % of wet sample)	17.52	9.03	87.79	73.19
Volatile solids (VS) (% of TS)	85.39	84.24	94.49	82.18
pH	8.66	8.63	8.67	8.63

Due to the characteristics (wet/dry) of substrates (i.e. sludge, wood chips, raw material, etc.) to the ice cream waste of the different waste variations, the moisture content differed significantly within a range of 7 – 89%.

The total solid (TS) percentage of the four samples differed significantly (Table 5-3) due to the differences in composition of the samples. Waste variation 1 consisted of 60% ice cream waste and 40% sludge. The sludge consists of waste ice cream and waste water. The addition of sludge has resulted in the TS of waste variation 1 being less than the TS of the ice cream only sample. Waste variations 2 and 3 had a higher TS values, mainly due to the addition of the ground up wood chips (variation 2 and 3) and raw material (consisting of sugar, vegetable fat, water, milk powder, cocoa powder and flavouring) in variation 3. The VS percentage (expressed as a percentage of the TS) were, however, relatively similar for all four samples, with waste composition 2 having the highest VS of 94.49% and waste composition 4 having the lowest VS of 82.18%.

The pH of all four samples were within the same range, ranging between 8.63 and 8.67. As mentioned in Section 5.1, the pH of the four samples were relatively higher than that measured for similar studies done on ice cream related waste, but within the same range than what is expected for dairy-related wastes (Xu *et al.*, 2018, Lisboa & Lansing, 2013 and Demirel *et al.*, 2004).

Section 5.3.3 attempts to draw correlations between the different physico-chemical characteristics (moisture content, TS, VS and pH) and the biomethane production of the different waste variations.

5.3.2. Biomethane output of the different waste variations (mixtures)

Table 5-4 and Figure 5-1 show the biomethane output of the ice cream only waste and the three waste variations in triplicate and their average with standard deviations, after being subjected to anaerobic digestion conditions for 28 days. Biomethane output was normalised according to the volatile solids (Nml CH_4 per kg of VS).

Figures 5-2 to 5-5 provide a more detailed account of the cumulative biomethane production over the 28-day period, while Figure 5-6 provides the cumulative biomethane production of the four different waste variations on the same graph to allow for comparison.

Table 5-4: Biomethane output (in Nml CH_4/kg VS) from ice cream waste (only) and the three waste variations measured in triplicate. The baseline value represents the biomethane output produced by the inoculum.

Waste stream	**Biomethane output (Cumulative methane production) Nml CH_4/kg VS**			**Standard deviation**	**Average biomethane output (Nml CH_4/kg VS)**	**Biomethane production potential equivalent, relative to ice cream only**
	Test 1	**Test 2**	**Test 3**			
Baseline	190.2	205.4	183.1	11.39	192.9±11.39	-
Ice cream waste only	1890	1997.3	1795.4	101.1	1894.2±101.1	1
Waste variation1 (60% Ice Cream, 40% ice cream sludge)	1957.6	1971.7	1965.8	7.1	1965±7.1	1.04
Waste variation 2 (60% ice cream, 20% sludge, 20% wood chips)	1077	1048.4	1133.1	43.1	1085.4±43.1	0.57
Waste variation 3 (60% ice cream, 20% raw material, 20% wood chips)	983.4	1095.7	995.8	61.6	1024.9±61.6	0.54

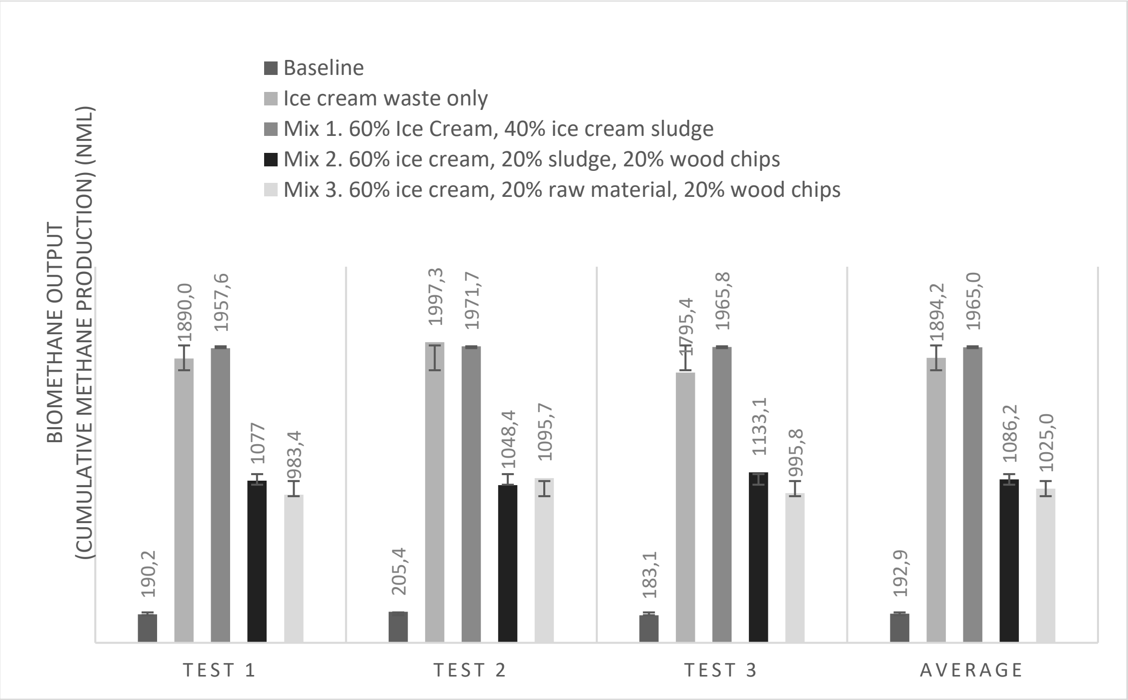

Figure 5-1: Biomethane output (in Nml CH_4/kg VS) from ice cream waste (only) and the three waste variations measured in triplicate.

When compared to ice cream only, waste variation 1 (with the 60% ice cream waste and 40% sludge composition) was the most optimal ice cream waste mixture. The mixture produced 1965±7.1 Nml of CH_4/kg VS, when compared to ice cream only, which produced 1894.2±101.1 Nml of CH_4/kg VS, which is about a 4% difference (if the standard deviation is not taken into account). Waste variations 2 and 3 produced less biomethane ranging between 1085.4±43.1 and 1024.9±61.6 Nml of CH_4/kg VS, respectively, which was approximately 43% and 46% less than the ice cream waste only sample.

Studies cited by Xu *et al.* (2018) on food waste mixed with different substrates have also shown that food wastes mixed with sludge with a relatively high moisture content had higher biomethane yields than food waste mixed with dry co-substrates or than food waste without any co-substrates.

According to Demirel *et al.* (2004), depending on the production sequences used in the ice cream factory, both ice-cream wastewater and ice-cream production residues had moderately variable characteristics and these particular characteristics had contrary impacts on the methane yields in terms of energy recovery through the anaerobic digestion process. Recovery of energy from ice cream wastewater alone appeared positive as long as acceptable buffering capacity was provided by exterior supplementation of buffering chemicals. However, energy recovery from ice-cream production residue alone did not seem possible, particularly due to high oil and grease, and $SO{-}_4^2$ content, which could considerably decline the methane yields or could cause termination of methane production. When wastewater and residue were assorted at a suitable ratio, and adequate buffering capacity was provided, anaerobic co-digestion of ice-cream wastewater and residue could produce methane as a source of renewable energy. However, the methane yields, and the potential energy recovery would intensely depend on the characteristics of both substrates. Figures 5-2 to 5-5 discuss the four waste composition variations and their biomethane production output over the 28-day test period. The three lines provided on each of the graphs represent the biomethane produced during the three tests (triplicate).

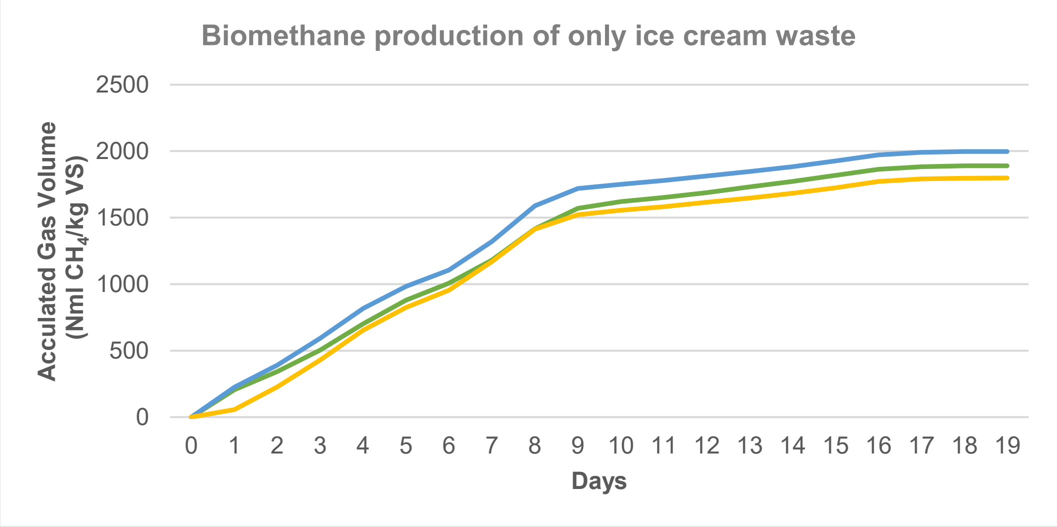

Figure 5-2: **Biomethane production of ice cream (only waste)**

As seen in Figure 5-2, for the ice cream only waste, biomethane was produced from day 1 and increase significantly around days 2 to 9. Biomethane production stabilised on day 18, with the biomethane yield remaining relatively consistent from day 18 to day 28.

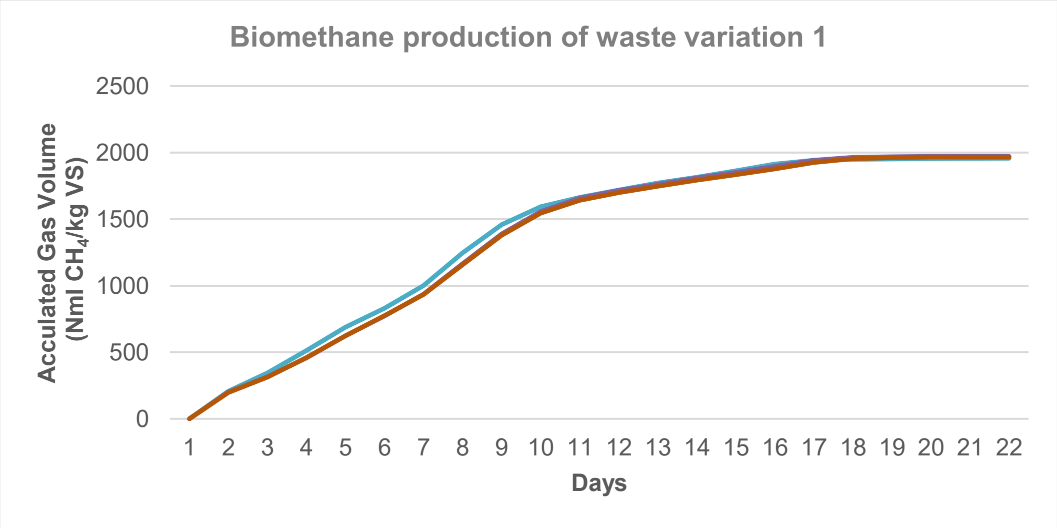

Figure 5-3: **Biomethane production of waste variation 1**

For waste variation 1 (60% ice cream, 40% sludge) (Figure 5-3), biomethane was produced from day 1 and started to increase significantly from day 2 to day 11. On day 19, biomethane production stabilised, with the biomethane production yield remaining relatively constant from day 19 to day 28.

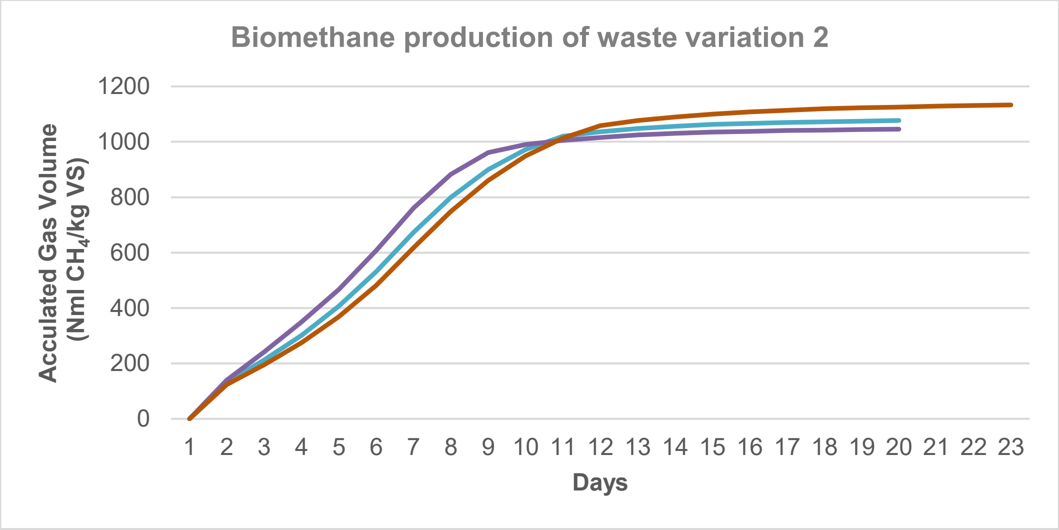

Figure 5-4: Biomethane production of waste variation 2

As seen in Figure 5-4, waste variation 2 (60% ice cream, 20% sludge, 20% wood chips) produced biomethane from day 1 and increased significantly from day 4 to day 10 (and 11). Biomethane production stabilised on day 13, with the biomethane yield remaining relatively consistent from day 13 to day 28.

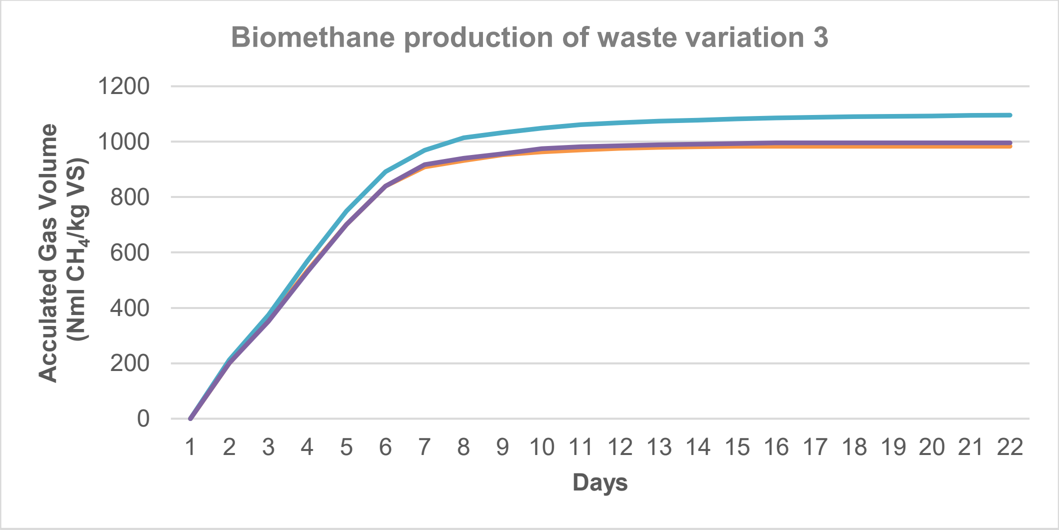

Figure 5-5: Biomethane production of waste variation 3

For waste variation 3 (60% ice cream, 20% raw material, 20% wood chips) (Figure 5-5), biomethane was produced from day 1 and started to increase significantly from day 2 to day 6.

On day 10, biomethane production stabilised, with the biomethane production yield remaining relatively constant from day 10 to day 28.

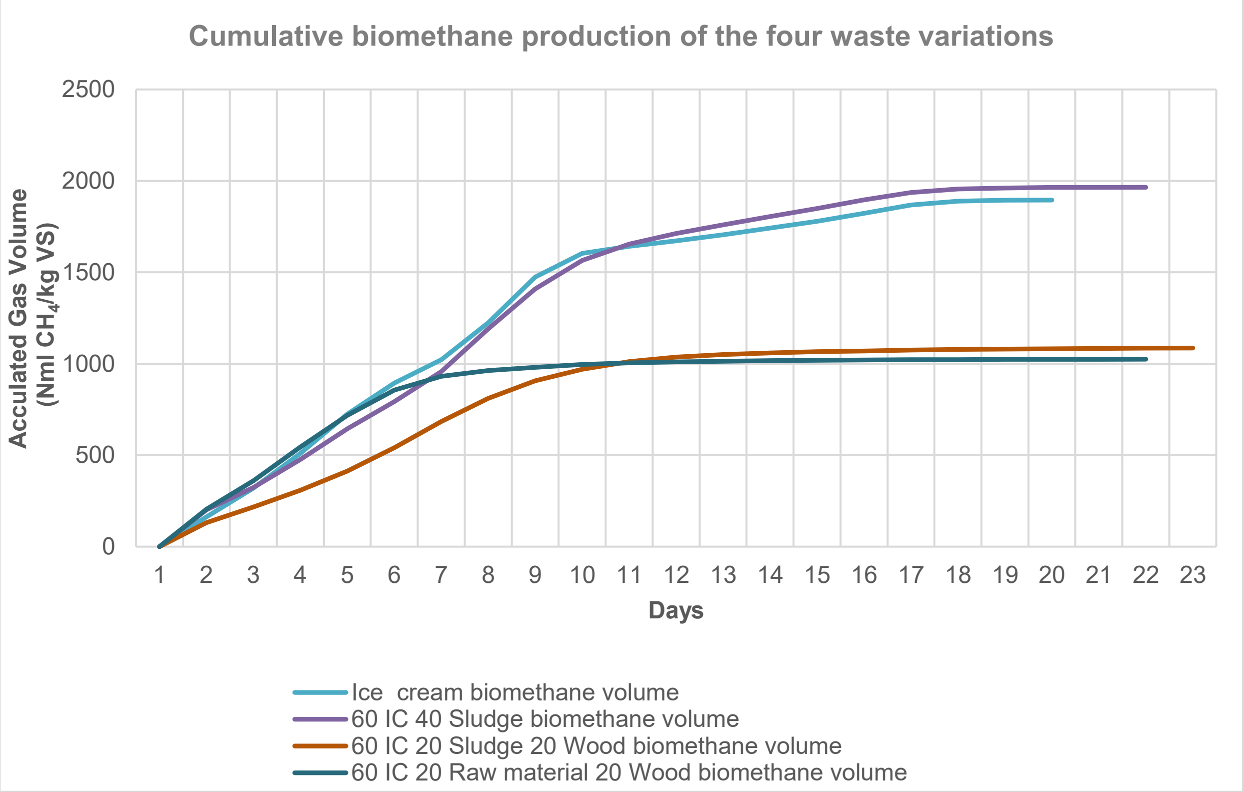

Figure 5-6: Summary of cumulative biomethane production of the four waste variations

Based on biomethane production (quantity), results indicated (Figure 5-6) that waste variation 2, (60% ice cream, with 40% ice cream sludge as a co-substrate) was the most optimal waste composition profile tested for this study. However, results waste variation 2 did not differ significantly from the ice cream only waste, in terms of cumulative biomethane production. Waste variations 2 and 3 produced about a half of the biomethane that the ice cream only waste and variation 1 produced and are deemed to be less suitable waste mixtures (as far as biomethane production was concerned). Ice cream only waste and waste variation 1 produced similar trends, with a rapid increase in biomethane production from day 2 up to 9 and 11 days, respectively, with biomethane production stabilising on days 18 and 19, respectively. Waste variation 2 showed a rapid increase in biomethane production between days 4 and 10, with biomethane production stabilising much sooner (when compared to ice cream only and waste variation 1), on day 13. Waste variation 3 was the mixture which showed the earliest stabilisation in biomethane production – with a rapid increase from day 2 to 6, and stabilisation from day 10 onwards.

Lisboa and Lansing (2013) have found similar results, where 58 to 84% of the biomethane was produced during the first 12 days, for all food waste with co-digestion substrates tested for biomethane production. El-Mashad and Zhang (2010) also concluded for biomethane production from dairy and other food wastes that after 20 days, approximately 90% and 95% of the final biogas yield could be obtained. These results likely explain why most dairy digestion systems have retention times between 20 and 30 days.

5.3.3. Correlation between moisture content, TS, VS, pH and biomethane production

To understand some of the reasons behind biomethane production potential and the characteristics of the four samples, the correlation coefficient between the average biomethane production and each of the waste variation characteristics data sets were determined (Table 5-5).

A strong positive correlation (correlation coefficient of 0.999) exists between biomethane production and moisture content (%). This means that (for this study), the higher the moisture content, the higher the biomethane production. This trend is also confirmed by Agency for Toxic Substances and Disease Registry (2001) who found that a higher moisture content brought about higher biomethane production. The reason for this is that waste with a high moisture content supports bacterial decomposition and chemical reactions within the substrate (Agency for Toxic Substances and Disease Registry, 2001).

When considering the correlation between biomethane production and TS and VS, both of these characteristics showed a strong negative correlation with biomethane production (correlation coefficient of -0.995 and -0.979, respectively). This means (for both parameters) that the higher the TS and VS content, the lower the biomethane production. When considering the TS/VS ratio, no significant correlation seemed to exist between the TS/VS ratio and biomethane production (correlation coefficient = 0.326). Varying results are reported in literature on TS/VS ratio and its correlation with biomethane production. Some authors have found that the lowest ratio corresponds to the lowest production of methane (i.e. a positive correlation) (Hill & Bolte, 2000), while others have found that a lower ratio may correspond to higher methane production (Oleszkiewicz & Poggi-Varaldo, 1997). The correlation between pH and biomethane production was also weak (correlation coefficient = -0.135).

Table 5-5: **Biomethane output (in Nml CH_4/kgVS) from ice cream waste (only) and the three waste variations measured in triplicate, showing the correlation between biomethane production and moisture content, TS, VS and pH.**

Waste stream	Average biomethane output	Correlation between moisture content (%) and biomethane production		Correlation between TS (% of sample) and biomethane production		Correlation between VS (% of sample) and biomethane production		Correlation between TS/VS ratio and biomethane production		Correlation between pH on biomethane production	
	Nml CH_4/kgVS	Moisture content (%)	Correlation coefficient	TS (%)	Correlation coefficient	VS (% of sample)	Correlation coefficient	TS/VS ratio	Correlation coefficient	pH	Correlation coefficient
Ice cream waste only	1894.2±101.1	79.48	0.999	20.52	-0.995	17.52	-0.979	1.17	0.326	8.66	-0.135
Waste variation1 (60% Ice Cream, 40% ice cream sludge)	1965±7.1	89.27		10.73		9.03		1.18		8.63	
Waste variation 2 (60% ice cream, 20% sludge, 20% wood chips)	1085.4±43.1	10.94		92.93		87.79		1.05		8.67	
Waste variation 3 (60% ice cream, 20% raw material, 20% wood chips)	1024.9±61.6	7.07		89.06		73.19		1.21		8.63	

It is, however, difficult to make deductions and accurate correlations between biomethane production and the characteristics of the waste variations from such a small sample size (only four samples). It was also not the intent (not linked to any of the research questions) to establish the correlation between the characteristics of the waste variations and biomethane production. An attempt to establish whether significant correlations exist was merely pursued to understand the possible reasons behind differences in biomethane production between the four different waste samples.

5.4. Results and discussion of RQ3: Supporting elements necessary for the successful implementation of WtE projects

Results related to RQ3: *What supporting elements are necessary for the successful implementation of WtE project?* These were mainly gleaned from the literature review. Chapter 4 (the literature review) discussed aspects related to successful implementation of WtE projects from South Africa and elsewhere in the world in detail. The primary data gathered during this study also addresses some aspects of RQ3. Section 5.4 will, therefore, only summarise the supporting elements necessary for the successful implementation of WtE projects, by focusing on two categories, namely (a) supporting management instruments; and (b) waste composition.

5.4.1. Management instruments supporting WtE projects

It is known that there is an energy- and landfill space crisis in South Africa, therefore creating and adopting environmental solutions that benefit both energy and waste is critical, this is an example of sustainable development through the use of biomethane energy from waste.

It is also noted for biomethane projects to be successful they need to consider and implement the below factors into the project plan:

- Government support regarding establishing and enforcing energy and waste legislation
- Proper planning is important, from the draft of the project to the construction and maintenance.
- Capital is required to approve the plans as well as construct and maintain the plant for future years.
- Sufficient and continuous organic waste is required and knowledge of the ratio of waste required to produce energy.

As mentioned above, the waste to energy plant has many factors to be successful but it also important to consider the input into the plants to ensure sufficient volume and composition as well as the atmospheric factors.

5.4.2. Waste composition

It is noted in this study and several other literatures that ice cream waste requires a substrate particularly sludge to increase its biomethane output. The atmospheric conditions are also important which will now be discussed. The high moisture content which supports bacterial decomposition and the production of biogas. Another is the oxygen content whereby biogas is formed under oxygen deficient conditions by anaerobic bacteria. There is an inverse relationship between oxygen content and biogas production – the lesser the oxygen content, the more the biogas produced. Particle size is also important as it is noted that smaller waste particle sizes are more favourable of biogas production than larger particles and lastly the temperature as higher temperatures can rise bacterial decomposition, volatilisation and chemical reactions - all of which may increase the biogas production potential (Agency for Toxic Substances and Disease Registry, 2001).

It is seen in this study that ice cream waste can generate biomethane, however the optimal formulation for biomethane production is ice cream with a substrate namely sludge, this relates to the favourable factor of moisture content increasing the biomethane production process.

5.5. Chapter Summary

This chapter discusses the results of the study and how it relates to previous literature. Many lessons learnt were discussed from the literature and how the results relate to the research questions and the interruption of the data. The next session will discuss the conclusions and recommendations.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1. Research question conclusions

This chapter will conclude on the research objectives of the study and also provides recommendations for further research.

6.1.1. Conclusions on Research question 1: Does waste from the ice cream factory have the *potential to produce biomethane* during anaerobic digestion?

The physico-chemical characteristics of ice cream waste (only) was similar to the physico-chemical characteristics of ice cream and other dairy wastes analysed by other authors (Xu *et al.*, 2018, Lisboa & Lansing, 2013 and Demirel *et al.*, 2004) which suggests that, based on physico-chemical properties (such as VS, TS, pH and moisture content), ice cream waste from the Ola ice cream factory should have the potential to produce biomethane.

Based on the biomethane output over a 28-day period, it was found that ice cream waste (only) had the potential to produce biomethane (1894.2±101.1 Nml CH_4/kg VS). The results of this study suggested a biomethane output, which was relatively high, when compared to similar studies done on ice cream waste. Derimel *et al.* (2004), for example, have reported cumulative methane yields of approximately 380 ml for ice cream production residue. Studies determining the biomethane output of ice cream waste are, however, limited, which makes comparison of biomethane yield, difficult.

Literature suggests that the addition of substrates to waste may increase biomethane production, therefore, research question 2 had the objective of determining the optimal waste composition ratio/profile, based on different waste variation mixtures from the Ola ice cream factory in Midrand.

6.1.2. Conclusions on Research question 2: What is the *optimal waste composition ratio/profile* that would produce the most (quantity) biomethane during anaerobic digestion?

The waste composition variations analysed to determine the optimal waste composition ratio/profile comprised of waste generally produce by the Ola ice cream factory and consisted of: ice cream waste only; ice cream waste mixed with ice cream sludge (60:40) (waste variation 1); ice cream waste mixed with ice cream sludge and wood chips (60:20:20) (waste variation 2); and ice cream mixed with raw material and wood chips (60:20:20) (waste variation 3). The analysis was limited to ice cream only and three other variations, based on cost and the profile of waste which could be reasonably and realistically expected from the factory, and results from literature.

The addition of ice cream sludge to the ice cream waste (waste variation 1) improved the biomethane production potential by 4% (from 1894.2 to 1965 Nml CH_4/kg VS), when compared to ice cream only. This finding supports the claims made in literature that the addition of certain substrates (such as waste water) may increase biomethane production.

The waste composition variations (variation 2 and 3) where wood chips were added, produced lower amounts of biomethane (1085.4±43.1 Nml CH4/kg VS and 1024.9±61.6 Nml CH_4/kg VS, respectively), when compared to ice cream only waste and waste variation 1.

Considering the cumulative biomethane output over a 28-day period, ice cream only waste and waste variation 1 produced similar trends, with biomethane production stabilising on days 18 and 19, respectively. Waste variation 2 showed a rapid increase in biomethane production between days 4 and 10, with biomethane production stabilising on day 13, whereas waste variation 3 already stabilised on day 10.

To explain the differences in biomethane production, the correlation coefficient between biomethane output and the physico-chemical characteristics, such VS, TS, pH and moisture content, of the waste variations was determined. The only significant positive correlation was found between biomethane production and moisture content (0.999), where the waste variations with a higher moisture content, produced a higher biomethane output. The reason for this is that waste with a high moisture content supports bacterial decomposition and chemical reactions within the substrate (Agency for Toxic Substances and Disease Registry, 2001; Derimel *et al.*, 2004). The lower moisture content in waste variations 2 and 3 were due to the addition of dry ingredients such as sugar and ice cream powder flavouring in the raw material, and wood chips.

TS and VS showed a strong negative correlation with biomethane production (correlation coefficient of -0.995 and -0.979, respectively), and when considering the TS/VS ratio, no significant correlation seemed to exist (correlation coefficient = 0.326). Varying results are reported in literature on TS/VS ratio and its correlation with biomethane production. Some authors have found that the lowest ratio corresponds to the lowest production of methane (i.e. a positive correlation) (Hill & Bolte, 2000), while others have found that a lower ratio may correspond to higher methane production (Oleszkiewicz & Poggi-Varaldo, 1997).

In terms of waste composition requirements, it is important to understand the characteristics of the waste that is considered to feed the WtE infrastructure. Within the anaerobic digestion context, the moisture content which supports bacterial decomposition and the production of biogas is important. Oxygen content whereby biogas is formed under oxygen deficient conditions by anaerobic bacteria need to be managed. Particle size is also important as it is noted that smaller waste particle sizes are more favourable for biogas production than larger particles. Lastly, temperature plays an important role in biodigestion, since higher temperatures can rise bacterial decomposition, volatilisation and chemical reactions - all of which may increase the biogas production potential (Agency for Toxic Substances and Disease Registry, 2001).

In conclusion, the results of the study indicated that ice cream waste has the potential to produce biomethane, and biomethane outputs from this study were similar to other dairy waste-related studies. The results suggest that the addition of ice cream sludge, which contains waste water from the ice cream manufacturing process, has the potential to improve biomethane production. This corresponds well with what have been reported by other authors.

6.1.3. Conclusions on Research question 3: What *supporting elements* are necessary for the successful implementation of WtE project?

Apart from understanding the optimal waste profile/mixture and other physico-chemical characteristics that play role in biomethane production, it is also important to understand the supporting environment that could make waste-to-energy projects successful or not. To understand these supporting elements, lessons were gleaned from WtE projects, more specifically anaerobic digestion projects, done elsewhere in the world. The main supporting elements that need to be considered include:

- Government support regarding establishing and enforcing energy and waste policy and legislation;
- Proper planning is important, from the draft of the project to the construction and maintenance to understand the opportunities and limitations of WtE projects;
- Capital support is required to approve the plans as well as construct and maintain the plant for future years;
- The necessary technical and technological expertise is required to commission and operate WtE projects within the operational and legislative requirements; and
- Sufficient and continuous organic waste (with the correct composition – as informed by RQ1 and RQ2) is required, supported by knowledge of the characteristics of waste necessary to produce energy.

As mentioned above, the waste to energy plant has many factors to be successful but it is also important to consider the input into the plants to ensure sufficient volume and composition as well as emissions to the atmosphere.

6.2. Recommendations for further research

This study sets a basis for future studies on biomethane production from dairy wastes, which has currently not been researched extensively in South Africa. The results of this study is useful as a starting point to assess biomethane production potential from wastes from other dairy industries in South Africa and elsewhere in Africa. A more varied spectrum of organic wastes and consideration of their physico-chemical characteristics is important to understand biomethane production.

It is recommended that more waste variations are analysed (with different components) to gain a better understanding of the different factors which may contribute to biomethane production. Increasing the waste variations would provide more data to support or challenge the finding that ice cream and sludge (waste variation 1) is the optimal waste profile.

The additional analysis of other physico-chemical parameters (other than VS, TS, pH and moisture content) may be useful to draw correlations between physico-chemical composition and potential for biomethane production.

This study was mainly aimed at understanding biomethane production from ice cream waste variations in the context of *anaerobic digestion* as a suitable technology for WtE. Future studies focusing on technologies other than anaerobic digestion for ice cream/dairy-waste to energy may be useful to provide a selection of technologies for consideration.

Although the waste management hierarchy advocates the avoidance, minimization, re-use and recycling of waste as preferred alternatives to treatment and energy recovery, this study did not aim to address the implementation of these strategies. The investigation of these strategies (as an alternative to treatment and recovery) need to be researched further.

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