

**THE DEVELOPMENT OF A FRAMEWORK FOR A
CLIMATE CHANGE STABILIZATION STRATEGY TO
ACHIEVE SUSTAINED CARBON EMISSION REDUCTION
FROM ORGANIC WASTE IN SOUTH AFRICAN
MUNICIPALITIES**

by

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Doctor of Philosophy

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Preface

The work described in this thesis was carried out through the School of Engineering, Programme of Civil Engineering, University of KwaZulu-Natal, Durban, from June 2019 to June 2023, under the supervision of Professor Cristina Trois.


These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

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I, Sameera Kissoon, declare that:

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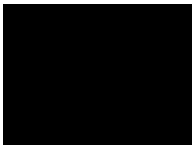
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DECLARATION 2: PUBLICATIONS

This thesis contains a compilation of manuscripts/published works whereby each chapter is an individual entity prepared as per journal' specification. Therefore, some repetition among chapters is unavoidable. The first author (student) was responsible for all data collection and manuscript preparation under the guidance of the second author (supervisor)

1. Kissoon, S. and Trois, C. 2023. Optimized organic waste management strategies for sustained carbon emission reduction and climate change stabilization in the Garden Route District of SouthAfrica. Waste Management in Developing Countries. Waste as a Resource Series. Eds. El Bari and Trois. Springer Nature (Switzerland). ISSN 2731-8222. 77-90. (Chapter 1). https://link.springer.com/chapter/10.1007/978-3-031-28001-6_5
2. Kissoon, S. and Trois, C. 2023. An assessment of sustained GHG emission reduction and the implications of policy implementation for the diversion of organic waste in the City of Cape Town.
3. Kissoon, S. and Trois, C. 2023. Preliminary development of a framework for an adaptable greenhouse gas mitigation strategy for South African Municipalities: A case study of the City of Cape Town Metropolitan Municipality and the Garden Route District Municipality.
4. Kissoon, S. and Trois, C. 2022. Plastic waste management for landfill space saving and GHG emission reduction in the Garden Route District Municipality. In proceedings of WasteCon 2022. Waste Management Conference. 3S Media. Johannesburg.

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Sameera Kissoon Date: 16 April 2024

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Executive Summary

According to the Global Carbon Atlas, South Africa is ranked as the 14th highest greenhouse gas emitter globally (Global Carbon Atlas, 2021). The waste sector is estimated to contribute to 4.8% of the total emissions across the country according to the 8th National Greenhouse Gas Inventory Report of South Africa (DFFE 2021). It is estimated that 76% of the total municipal solid waste in South Africa is disposed of into landfill facilities (DFFE, 2021). Landfilling and waste management as a whole are regulated through the National Environmental Management: Waste Act and the National Waste Management Strategy (NWMS). In an effort to determine and reduce the impacts of various sectors' contribution to global warming, the South African National Department of Forestry, Fisheries and the Environment (DFFE) commissioned the Mitigation Potential Analysis (MPA) study. The MPA methodology was developed to guide major sectors such as agriculture, transport and waste among others in understanding their contributions to global warming as well as to propose mechanisms at a national level to reduce the impacts of key sectors on global warming (DFFE 2018).

The purpose of this study directly aligns with the goals of the MPA in efforts to mainstream the discourse climate change in waste management decision making, through the development of a preliminary framework to guide greenhouse gas mitigation from waste management activities using a bottom up approach starting at municipal level. The overarching hypothesis of this study is that municipalities in South Africa are the main custodians of solid waste in the country and can therefore play a key role in the effective mitigation of greenhouse gases (GHG) in the waste sector. However, some of the major gaps identified in understanding the exact contributions of the waste sector on climate change is the availability of good quality data as well as the lack of funding, capacity and know-how at municipal level to conduct GHG emissions and mitigation studies. The main aim of the study is to determine the annual contributions of the organic waste fraction to climate change over the next 50-years in two case study municipalities: one district municipality representative of a district municipality at provincial level, and one metropolitan municipality representative of the 8 metropolitan municipalities of South Africa.

A second aim is that to develop a framework in support of the strategy for the stabilization of climate change from the management of organic waste at municipal level. This was conducted through the identification of pathways for the diversion of the organic waste fraction of

municipal solid waste in the selected case study municipalities using the currently available data and forecasting techniques.

In order to achieve these aims, the objective of the study encompassed four key components: data collection; a waste stream analysis and identification of waste amounts; an assessment of carbon emissions and reductions from organic waste in the case study municipalities and lastly the development of a framework for a greenhouse gas mitigation strategy to achieve climate change stabilization.

This study assessed the GHG emissions and emission reduction potential from the organic food waste fraction and the garden refuse fraction in the Garden Route District (GRDM) and City of Cape Town (CoCT) municipalities in the Western Cape, South Africa. These case study municipalities were selected based on their individual contributions to the total population of the Western Cape and their contributions to the provinces gross domestic product (GDP). The Waste Resource Optimization and Scenario Evaluation (WROSE) model is a life cycle assessment based model which assists the user in determining which integrated waste management scenario is most suitable, specific to a municipality's needs. This is based on the selection of appropriate technology pathways to divert waste from landfill as well as implement alternative waste treatment solutions. The study began with first advancing the WROSE model through the development of an algorithm to enable the model to perform long term greenhouse gas forecasting, This was done through the use of, waste generation data which was forecast in line with the total population growth. Using these identified figures and IPCC emission factors, the study assessed the potential GHG emissions and emission reduction achievable from the extraction of the organic waste fraction and garden refuse fraction in both case study municipalities. Thereafter, the study employed the WROSE model for the identification of appropriate mitigation pathways and alternative waste treatment technology options (Trois and Jagath, 2011 and Trois et al., 2023). The study further assessed the viability of the organic food waste fraction at varied intervals of recovery for use in applicable integrated waste management technology options such as landfilling with gas recovery and anaerobic digestion that are geared towards decarbonisation in the solid waste sector. A multicriteria decision analysis technique was incorporated for the development of the preliminary framework for climate change mitigation from municipal solid waste.

In addition this study outlined a comparative analysis conducted between the two case study municipalities to determine how population affects waste generation and ultimately GHG

emission contributions in the waste sector. The key finding is that existing municipal infrastructure is not designed for separated collection of the organic food waste fraction, nor is there existing infrastructure for the treatment of the organic waste fraction of municipal solid waste. Therefore, this study proposes a framework which adopts a phased approach to GHG emission reductions through the optimization of existing waste management facilities and the development of necessary infrastructure for the management of organic waste fractions over a 50 year period to achieve carbon emission reductions in the waste sector.

This study developed a novel bottom-up framework for a greenhouse gas mitigation strategy that will contribute to climate change stabilization using immediate-term, short-term, medium-term and long-term interventions that can be applied at municipal level in order to contribute to national emission reduction targets. This bottom-up approach is aimed at guiding the developments of individual greenhouse gas mitigation mechanisms at a local municipal level which contributes to the larger system of meeting NDC targets. The study is also the first application of a Tier 2 for the MPA approach which embodies national methodologies, in this case the WROSE tool as a country-specific model and IPCC emission factors to determine the GHG emissions and reduction potentials from the waste sector. These reductions can be achieved through the introduction of separated collection systems at local municipal level and technology options such as a material recovery facility, anaerobic digestion and composting in a staged approach. The framework will allow decision makers to develop a greenhouse gas mitigation strategy that will be applicable to the needs of the municipality based on existing infrastructure and available waste quantities which will ultimately contribute to meeting the needs of the NDC targets for South Africa using a bottom-up approach.

Table of Contents

Preface	ii
Declaration 1 Plagiarism.....	iii
Declaration 2 Publications	v
Acknowledgements.....	vii
Executive Summary.....	viii
List of Figures	xiv
List of Tables.....	xvii
Chapter 1 Introduction.....	1
1.1 Preamble.....	1
1.2 Background.....	1
1.3 Motivation.....	4
1.4 Research Question.....	6
1.4 Aims.....	7
1.4 Objectives	7
1.5 Technical and Scientific Contributions.....	7
1.6 Structure of the Thesis	7
1.7 References.....	9
Chapter 2 Literature Review	12
2.1 Overview of waste management globally.....	12
2.2 Municipal solid waste management best practice.....	15
2.3 Technologies related to the management of solid waste.....	16
2.4 Status quo of waste management in South Africa.....	18
2.5 South African governance structures.....	19
2.6 Waste management legislative instruments in South Africa.....	20
2.7 Integrated waste management models.....	23
2.8 Waste stream assessment.....	27
2.9 Chapter summary.....	28
2.10 References.....	28
Chapter 3 Methodology.....	36

3.1 Structure of methodological approach.....	36
3.2 Overview of waste management decision support tools.....	37
3.3 Existing WROSE model.....	37
3.4 Advancement of the WROSE model.....	42
3.5 Climate mitigation strategy framework development	45
3.6 Chapter summary.....	50
3.7 References.....	50

Chapter 4 Optimized Organic Waste Management Strategies for sustained carbon emissions reductions and climate change stabilization in the Garden Route District of South

Africa.....	51
4.1 Abstract	51
4.2 Introduction	52
4.3 Study Area	54
4.4 Methodology.....	56
4.5 Results and Discussion.....	62
4.6 Conclusion and recommendations for future research.....	67
4.7 Bibliography.....	67

Chapter 5 An assessment of a greenhouse gas mitigation strategy for sustained GHG emission reduction and the implications of policy implementation for the diversion of organic waste in the City of Cape Town.....

71	71
5.1 Abstract	71
5.2 Introduction	72
5.3 Case Study Area	73
5.4 Methodology.....	76
5.5 Results and Discussion.....	82
5.6 Conclusion	91
5.7 References.....	91

Chapter 6 A comparative analysis of the GHG emission reduction potential from organic food waste fractions in a district municipality versus a metropolitan municipality: A South African Case Study.....

94	94
----	----

6.1 Abstract	94
6.2 Introduction	95
6.3 Study Area	96
6.4 Methodology.....	98
6.5 Results and Discussion.....	103
6.6 Conclusion	111
6.7 References.....	111
Chapter 7 Conclusion and Recommendation	114
7.1 Introduction	114
7.2 Key findings and conclusions.....	115
7.3 Limitations of the study	116
7.4 Recommendations.....	116

List of Figures

Chapter 2

Figure 1. WROSE scenarios schematic.....	26
--	----

Chapter 3

Figure 1: Scenario 1.....	38
Figure 2: Scenario 2A.....	38
Figure 3: Scenario 2B.....	39
Figure 4: Scenario 3.....	39
Figure 5: Scenario 4.....	40
Figure 6: Scenario 5.....	40
Figure 7: Example of existing WROSE model outputs for 2020.....	42
Figure 8: Example of advanced WROSE model outputs for long term forecasting per scenario.....	45
Figure 9. Example of a value tree for a climate mitigation co-benefits MCDA process.....	46

Chapter 4

Figure 1: Average domestic waste profile in the Garden Route District Municipality.....	55
Figure 2: Garden Route district municipality, South Africa.....	55
Figure 3: WROSE scenarios schematic.....	58
Figure 4: Projection of food waste and garden refuse tonnages in the Garden Route District Municipality from 2013 to 2070.....	62
Figure 5: 50-year projections of MTCO ₂ eq emissions for the disposal of food waste and garden refuse to landfill (BAU).....	63
Figure 6: Climate change stabilisation wedge for 50-year projections: Comparison between food waste to landfill (BAU) versus food waste to Anaerobic Digestion.....	64
Figure 7: Climate change stabilisation wedge for 50-year projections: Comparison between food waste to landfill (BAU) versus food waste to composting.....	65
Figure 8: Comparison between 50-year projections of GHG emissions for food waste to landfill (BAU) versus food waste to composting.....	65

Figure 9: Projected carbon emissions reductions for various percentages of viable food waste fractions for AD.....	66
--	----

Chapter 5

Figure 1: Map of the City of Cape Town Metropolitan Municipality.....	74
Figure 2: Waste profile of the household waste fraction in the CoCT.....	75
Figure 3a: MSW per capita and b. MSW per capita and GDP per capita in the City of Cape Town.....	76
Figure 4: WROSE scenarios schematic	79
Figure 5: Projection of population and waste tons over a 50 year period in the City of Cape Town.....	83
Figure 6: Projection of waste tons for food waste and garden refuse over 50 years in the City of Cape Town.....	84
Figure 7: 50 Year projection of MTCO ₂ eq emissions for the disposal of food waste and garden refuse to landfill for the CoCT.....	85
Figure 8. Methane emissions and emissions reduction potential from food waste to landfill with landfill gas extraction in MTCO ₂ eq	86
Figure 9: Methane emissions in MTCO ₂ eq produced from food waste to landfill and reduced from food waste to AD CoCT.....	87
Figure 10: Climate change stabilisation over a 50-Year period for the CoCT from food waste to composting	88
Figure 11: 50 year projection of GHG emission reduction from composting of garden refuse for the CoCT	88
Figure 12: Methane emissions in MTCO ₂ eq reduced from the implementation of policy targets.....	89
Figure 13: Methane emissions in MTCO ₂ eq reduced from food waste to AD in the CoCT over a 50 year period at various recovery rates.....	90

Chapter 6

Figure 1: Map of the Western Cape Province.....	97
Figure 2: Waste profile of the City of Cape Town and the Garden Route District Municipality.....	98

Figure 3: WROSE scenario 1, 2 and 4 schematic.....100

Figure 4: Population projection for the CoCT and GRDM over a 50 year period.....104

Figure 5: Total waste projection for 50 years for the CoCT and the GRDM.....105

Figure 6: Total organic waste projection for the CoCT and GRDM for the next 50 years.....105

Figure 7: Methane emissions in MTCO₂eq produced from the disposal of food waste to landfill in the GRDM and CoCT over a 50 year period.....106

Figure 8: Methane emissions in MTCO₂eq reduced from food waste to landfill with landfill gas extraction GRDM and CoCT over a 50 year period.....107

Figure 9: Methane emissions in MTCO₂eq reduced from food waste to AD in the GRDM and CoCT over a 50 year period.....108

Figure 10: Methane emissions in MTCO₂eq reduced from food waste to AD in the GRDM and CoCT over a 50 year period at a phased approach from 5%-40%.....109

List of Tables

Chapter 2

Table 1. Comparison of waste characterisation streams per municipality versus national State of Waste Report.....	27
---	----

Chapter 3

Table 1. Summary of waste management decision support tools.....	37
Table 2. Criteria for developing a climate mitigation strategy.....	48

Chapter 4

Table 1. Historical population and waste tonnages figures.....	59
Table 2. Table of emission factors.....	61

Chapter 5

Table 1. IPCC emission factors.....	81
-------------------------------------	----

Chapter 6

Table 1: IPCC emission factors.....	102
Table 2: Phased GHG emissions at 5-year intervals for the CoCT and GRDM.....	108
Table 3: Proposed framework for the development of a greenhouse gas mitigation strategy.....	110

List of abbreviations

AD – Anaerobic digestion

CO₂ – Carbon dioxide

CDM – Clean Development Mechanism

CH₄ – Methane

COCT – City of Cape Town

DEA – Department of Environmental Affairs

DFFE – Department of Forestry, Fisheries and Environment

DAT – Dome aeration technology

EASETECH - Environmental Assessment System for Environmental TECHNOLOGIES

GHG – Greenhouse gases

GRDM – Garden Route District Municipality

GWP – Global warming potential

IPCC – Intergovernmental Panel on Climate Change

IWMP – Integrated waste management plan

LFG – Landfill gas

LCA – Life Cycle Assessment

LSS – Landfill space savings

MBT – Mechanical Biological Treatment

MPT - Mechanical Pre-Treatment

MRF – Material recovery facilities

MSW – Municipal solid waste

MTCO₂eq – Metric tons of carbon dioxide equivalents

MW – Mega Watt

RE – Renewable Energy

UKZN – University of KwaZulu-Natal

US EPA – United States Environmental Protection Agency

WARM – Waste Reduction Model

WRATE - Waste and Resources Assessment Tool for the Environment

WROSE – Waste Resource Optimisation Scenario Evaluation WSA – Waste stream analysis

CHAPTER 1

1. Introduction

1.1 Preamble

This thesis is structured as a “thesis by papers”. The body of the thesis is a compilation of research publications under review, accepted or published. Chapter 1 presents an Extended Introduction to guide the reader through the rationale of the study and the interlinks among the various publications.

1.2 Background

In excess of two billion metric tons of municipal solid waste is produced globally and this is expected to grow by two fold by 2050 (Gautham & Agarwal, 2020). Subsequently, solid waste is a source of greenhouse gas emissions which contributes to global warming. Climate change has an impact and poses many challenges socially, economically and environmentally across the globe. In 2015, the United Nations Framework Convention on Climate Change (UNFCCC) adopted a goal aimed at the reduction of global warming to 2 °C above pre-industrial levels (UNFCCC, 2015). At the 21st Conference of the Parties (COP21) the Paris Climate Agreement was established, which thereby aligned nations toward the goal of combating climate change (Powell et al, 2018). In order to achieve the goals of the Paris Climate Agreement, adhering nations agreed on the Nationally Determined Contributions (NDCs) that specify emission mitigation goals and climate change adaptation strategies specific to each country’s context. The NDCs represent the effort of each of the participating countries to reduce national emissions through the implementation of applicable domestic climate mitigation and adaptation measures.

However, the discourse on climate change in developing countries is overshadowed by more immediate priorities such as poverty eradication, food security, water security and health care among others (HalsnæsK and Verhagen, 2007). Although climate mitigation is not seen as an immediate priority, the impacts of climate change has the potential to exacerbate existing issues such as food and water security. Therefore, the effectiveness of development strategies cannot overlook the synergy between development and climate change. South Africa, similarly to other developing countries is vulnerable to the impacts of global warming. This can be seen in historic rainfall trends in the country, from intense floods to drought affected areas. (DEA

2017). Furthermore, according to the Global Carbon Atlas, South Africa is ranked as the 14th highest greenhouse gases (GHG) emitter globally (Global Carbon Atlas, 2022). Therefore, it is of high importance to the South African Government to balance economic growth with the sustainable use of resources in an attempt to effectively tackle the issue of climate change (DEA, 2017). The most harmful of all greenhouse gases (GHG's) are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), whereby CH₄ emissions is said to be 28 times more harmful than CO₂. The waste sector and its contribution to GHG emissions have been identified as an important component to global warming due to the emissions resulting from municipal landfills and other waste management processes (Powell et al, 2018).

In recent years, waste generation in South Africa has been on the rise, the result of which has been an increase in the amount of waste disposed of into landfill. Most landfill facilities in South Africa are not managed in line with national regulation. South Africa still faces the issue of non-engineered and unlicensed landfill facilities; further to this, 87% of South African municipalities does have the necessary infrastructure or required capacity to implement effective waste minimization strategies (Nyika et al, 2020). Godfrey and Oelofse, 2017 attribute this to solid waste management being poorly funded and coordinated. Some of the key issues linked to waste management in South Africa include, licensing of waste management activities, poor collection services, illegal dumping among others (Nyika et al, 2020). South African municipalities lack proper equipment, infrastructure and waste treatment centres, all of which contributes to the challenges of achieving waste minimisation or diversion. In addition to the sustainable management of municipal solid waste, the waste sector contributes to GHG emission and the ultimately global warming. According to the 8th National Greenhouse Gas Inventory Report, it is estimated that the South African waste sector contributes to over 19 million tonnes of CO₂eq per year (NIR, 2021). This equates to approximately 4.8% of the total GHG emissions for the country. Methane emissions (CH₄) from the waste sector equates to approximately 36.5% of the total methane emissions in South Africa (NIR, 2021). Therefore the South African Government has developed legislative instruments, policies and models to manage the contributions of specific sectors to climate change. Since 2008 the South African Department of Forestry, Fisheries and the Environment (DFFE) have developed the National Environmental Management: Waste Act and the National Waste Management Strategy for the sustainable management of solid waste in the country. The DFFE has also developed the Mitigation Potential Analysis (MPA) model to support the work around climate change mitigation. The MPA model provides short; medium -and long term assessments on the

country's mitigation potential of various sectors such energy, agriculture and waste among others. The MPA model provides government with viable and cost-effective options to reduce GHG emissions in various sectors of the economy (DFFE, 2022).

The MPA model projects national GHG emissions in various sectors using the three scenarios outlined below.

- A '**Without Measures**' (**WOM**) projection of emissions from 2000 to 2050 assuming that no climate change mitigation actions have taken place since 2000.
- A '**With Existing Measures**' (**WEM**) projection, which incorporates the impacts of climate change mitigation policies and measures implemented to 2019.
- A '**With Additional Measures**' (**WAM**) projection, which assumes that existing, pipeline and potential future climate change mitigation policies and measures are implemented.

(DFFE, 2022)

Such instruments drive the shift towards sustainability and decarbonisation in the South Africa which incorporates various scopes of emissions. According to the Greenhouse Gas protocol the scopes of emissions include:

Scope 1 - Direct company owned or controlled emissions at the source

Scope 2- Emissions associated with energy consumed by a company

Scope 3- Indirect emissions associated with company activities not owned or controlled by a company

However, despite the development of instruments such as the MPA, the accurate implementation of integrated waste management strategies for appropriate management of municipal solid waste for climate is heavily reliant on the availability of good quality data in the waste sector. The paucity of data is a key challenge in the South African waste sector, combined with outdated waste characterisation studies, additionally, the methods of data collection and reporting differs from one municipality to the next. Furthermore, municipalities lack the necessary infrastructure, financial and human resources and to implement immediate interventions that will reduce the impact of the waste sector on climate change. This underpins some of the key gaps and challenges posed in the development of an implementable greenhouse gas mitigation strategy which will result in sustained GHG emissions reductions and contribute to climate change stabilization. The points above, form the basis for the conceptual framework

of the study which is further unpacked in the literature review chapter. The main aim of the study is to mainstream the concept of climate change modelling into the waste management decision making landscape as well as the broader discourse of waste management activities. The purpose of which is to embed climate considerations into the waste management decision making process. In determining the long term contributions of the organic waste fraction on greenhouse gas emissions in two case-study municipalities, one district municipality and one metropolitan municipality. This study seeks to bridge the gap between integrated waste management strategy development and achieving climate change mitigation from the municipal solid waste sector through GHG emissions reductions and how to translate these actions into the overall discourse of the national climate mitigation targets and strategies. Subsequently, to develop a framework that will guide the strategy for the stabilization of climate change from organic waste at municipal level. This study is part of a larger research project conducted by the SARCHI Chair in Waste and Climate Change at UKZN aiming at developing a comprehensive climate change stabilisation strategy for the South African waste sector.

1.3 Motivation

According to the 2022 National Inventory Report (NIR,2022), the gaseous emissions from solid waste disposal has increased by 34.1% since 2000 (DFFE 2022). The waste sector in South Africa has the capability to contribute towards a renewable energy source which will also mitigate the country's contribution to global warming. Municipalities in South Africa are the main custodians of solid waste in the country and can therefore play a key role in the effective mitigation of GHG's in the waste sector. However, South African municipalities lack the financial and human resources to conduct GHG emission contribution and reduction studies. The quantification of GHG emissions from the waste sector need to be assessed within the wider context of integrated waste management systems within a region. This is to appropriately determine the GHG emissions and reduction potential to climate change (Friedrich and Trois, 2013)

The UNFCCC (2009) has developed a resource guide to assist developing countries in conducting GHG inventories. The guide proposes a tiered approach for determining the GHG emissions contributions. These tiers are methodologies that can be used to estimate emissions based on availability of data, emission factors, financial and human capital to conduct the study

and lastly the desired level of detail. The higher the tier approach, the higher the level of complexity of the analysis:

- Tier 1: This incorporates IPCC default (non-specific) emission factors with the least disaggregated data;
- Tier 2: This requires more detailed data and incorporates country specific methodologies consistent with the IPCC guidelines;
- Tier 3: This the most complex level of details as it incorporates country specific emission factors and a country specific methodology (UNFCCC, 2009).

The overall purpose of this study is to strengthen the way South Africa measures GHG emissions from the waste sector as well as to strengthen how mitigation strategies are applied. Both the MPA and NDCs processes operate under a Tier 1 approach, which incorporates the use of default emission factors such as the IPCC emission factors and high level disaggregated data to determine GHG emissions at a national level from all sectors. This study aims to begin the transition from a Tier 1 to a Tier 3 approach which embodies country specific emission factors and a country specific integrated waste management model specifically looking at the organic fraction of Municipal Solid Waste (MSW). This study offers advancements in the development of country-specific integrated waste management models at municipal level which in this case is the WROSE model. The WROSE model was developed as a zero-waste model taking into consideration the collection and disposal of unsorted MSW to landfill (business-as-usual), followed by the introduction of technology options applicable to a developing countries context (Trois and Jagath, 2011; Trois et al., 2023). The WROSE model uses waste quantities as activity data which is input into the model, the outcome of which is scope 1 emissions or emission reduction potential in MTCO₂eq from various alternative waste management scenarios. The WROSE model considers only the emissions from the year of which the activity data is sourced. Therefore, this study aims to advance the WROSE models forecasting capabilities which will assist in long term emissions and reduction predictions from waste management activities. The study is also tests the efficacy of the first application of a Tier 2 approach for organic waste management, which includes non-country specific emission factors but a country specific model, in the South African context. In order to mainstream the discourse of climate change mitigation in the waste sector, this study, through simulations, will

also assess the impact of municipalities in meeting the goals set out in the MPA and NDCs and in doing so attempt to fast track the transition from a Tier 1 to a Tier 3 approach.

However, the efficiency and sustainability of waste management is influenced by multiple variables, including the measure and composition of waste among others (Stevanović-Čarapina et al., 2019). Ferronato et al, 2019 proposed the use of a selection of technology options as the most efficient way to reduce the global warming potential of sanitary landfills as well as increasing the lifespan of the landfill, this includes separation at the source. Therefore it is essential to this research to incorporate a selection of appropriate waste treatment technology scenarios and efficient integrated waste management strategies which will provide an opportunity to reduce costs, maximize energy production from waste, increase waste diversion from landfills, reduces GHG emissions, and minimizes environmental impacts through the extraction of problem waste streams from reaching landfills (Levis et al., 2013).

In 2019, the DFFE posed a ban on all liquid waste to landfill with a moisture content of >40% under the Norms and Standards for Disposal to landfill. The impact of which is the Western Cape Province issuing a ban on organic waste to landfill which has a moisture content of >40% to align with the Norms and Standards for Disposal to landfill set by National Government. Thus the overall aim of this study is to utilise the WROSE model and available data sources to determine the potential climate contributions of the organic waste fractions from the municipal solid waste sector in the Western Cape Province focusing on the City of Cape Town (CoCT) and the Garden Route District Municipality (GRDM). Thereafter, to develop a framework for a greenhouse gas mitigation strategy that is applicable to the CoCT and GRDM that can be replicated by the rest of the region to contribute towards climate change mitigation. This will be achieved through the identification of pathways for the diversion of the organic waste fraction of municipal solid waste in the selected case study municipalities using the currently available data and forecasting techniques.

1.4 Research Questions

- 1) What is the contribution of the organic waste fraction from the municipal solid waste sector to greenhouse gas emissions in the Western Cape Province with a particular focus on the City of Cape Town and the Garden Route District Municipality.
- 2) What technology portfolio can be employed to stabilize GHG emissions in City of Cape Town and the Garden Route District Municipality.

- 3) How can the implementation of these technologies translate into actionable steps in achieving greenhouse gas mitigation for climate change mitigation.

1.5 Aim

The aim of this study is to develop a framework through which greenhouse gas mitigation can be achieved for the Western Cape Provinces' municipal solid waste sector for the next 50 year focusing on the organic waste fractions.

1.6 Objectives

- a) To determine the GHG emissions from the municipal solid waste sector in the CoCT and GRDM without any interventions (Business-As-Usual) over the next 50 years.
- b) To determine GHG emission reduction potential through the extraction of organic waste out of the municipal solid waste stream in the next 50 years.
- c) To develop a framework to achieve climate change that is applicable to the greater Western Cape Province and ultimately the rest of South Africa.

1.7 Technical and Scientific Contributions

The most important scientific contribution to emerge from this study is the optimization of the methodology used to calculate GHG emissions in the waste sector using a Tier 2 approach. This contributes directly to the development of a bottom up framework for greenhouse gas mitigation that can be replicated or adapted across all South African municipalities using existing waste characterisation data. The greenhouse gas mitigation strategy has the potential to provide South African municipal officials with a mechanism to reduce the impact of the municipal solid waste sector on climate change and contribute to meeting NDC targets.

1.8 Structure of the Thesis

This thesis is a compilation of scientific publications and is structured into 6 chapters, including 1 published paper in its existing form and 2 manuscripts under review for publication, it also includes a peer-reviewed conference publication in Annexure 1. Chapter 1 is an extended introduction which provides a contextual background to the study which includes the motivation, aims, objectives as well as key research questions to be answered by the study.

Chapter 2 is a literature review and includes an assessment of the applicable waste policies and legislation to the management of municipal solid waste in South Africa. The identification of

important gaps that form the basis for the study. A comparison of various waste management models available globally provided insight into the tools available to calculate GHG emissions. One key finding was that, there are no mandatory requirements for conducting a waste characterization study at municipal level or landfill sites. Furthermore reporting categories for waste data are not standardised.

Chapter 3 forms the basis of this research and presents a detailed analysis of methane emissions reduction potentials for the development of a framework for a greenhouse gas mitigation strategy in the GRDM using the WROSE model and IPCC carbon emission factors. GHG emission reduction potential in the GRDM over a 50-year period was analysed. The introduction of mitigation pathways such as the implementation of alternative waste treatment technologies such as anaerobic digestion and composting were considered. The simulations of GHG emissions were considered with no interventions in place which depicts the direct result if the global warming potential of methane emissions from landfills over a 50-year period. Waste generation rates are projected to triple in the next 50-years with no interventions in place. In line with the increase of waste generation rates, is the increase of GHG emissions which also triple in 50 years. The introduction of anaerobic digestion as a waste treatment method for the food waste fraction and composting of the garden refuse fraction shows the potential for the stabilization of GHG emissions to current levels over a 50 year period. This study informs the development of a GHG emission mitigation strategy which will contribute towards future integrated waste management planning for municipal solid waste in the GRDM.

In order to develop a framework for an adaptable greenhouse gas mitigation strategy, a similar study to that of the GRDM was conducted for the organic food waste fraction in the City of Cape Town and is detailed in Chapter 4. The City of Cape Town, falls within the jurisdiction of the Western Cape Province, which has imposed a ban on organic waste from landfill by 2027 (DEA&DP, 2022). The results of this study incorporates 3 key components, the first being the assessment of GHG emissions from the disposal of the total organic food waste fraction to landfill versus the introduction of Anaerobic Digestion (AD) as a mechanism for the treatment of organic food waste. The second is the implications of policy implementations on GHG emissions and emission reduction potential. This is through the assessment of GHG emission reductions achievable from the banning of organic waste from landfill at a rate of diversion of 50% of the organic waste fraction by 2022 and the diversion of 100% of the organic waste fraction by 2027. Lastly, results looked at the GHG emission reduction that can be achieved

through the assessment of viability of the food waste fraction for use in AD in intervals from 5% to 40%. The results from this chapter determined that municipalities do not currently have the necessary infrastructure to treat organic waste fractions to substantially reduce contributions to global warming. Therefore, there is a need for the development of a phased strategic approach to allow for the development of infrastructure and staggered recovery rates of organic waste to achieve sustained carbon emission reduction.

The 5th chapter draws on the outcomes of chapters 3 and 4 and presents a comparative analysis of the population, waste generation and related GHG emissions between a district municipality and a metropolitan municipality. The key outcome of the study was that municipalities do not currently possess the capacity to divert the entire food waste fraction from landfill. Therefore, in order to achieve sustained GHG emission reduction, a phased approach was considered, whereby both municipalities gradually increase the recovery rate of the organic food waste fraction by 10% every 10 years to increase the emission reduction achievable. Using this proposed phased approach, a framework for the development of a greenhouse gas mitigation strategy is recommended for the organic waste fraction of the solid waste sector. This encompasses, short-, medium- and long-term mechanism to achieve long term climate change stabilization.

Chapter 6 outlines the conclusions, limitations and recommendations of the study.

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Chapter 2 - Literature Review

This chapter outlines a contextual overview of MSW management, both globally and locally (in South Africa). This chapter assesses various waste management technologies and the institutional mechanisms relevant to waste management in South Africa with particular emphasis on applicable legislation. Thereafter a range of waste management tools are assessed.

2.1 Overview of waste management globally

Due to socio-economic statuses, geographic conditions and technological developments, there is no single standard solution for the management of municipal solid waste across the globe. In first world countries like United States of America, solid waste management facilities are under scrutiny by regulators to drive the reduction of GHG emissions. Whereas in less developed instances such as Pakistan, the collected MSW is disposed of into open dumps and unspecified landfills (Michel et al, 2021). More than 50% of collected waste is improperly managed in developing countries (Godfrey et al, 2019).

A study conducted by Thanh and Matsui (2013) looked at the reduction of GHG emissions in eight cities Vietnam, the study assessed scenarios for the treatment of MSW. The outcome of the study determined that the most suitable alternative for the management of MSW is incineration with energy recovery. Similarly, a LCA study conducted by Cherubini et al. (2009) assessed the different waste disposal strategies in the city of Rome (Italy). That study determined that the disposal of waste to landfill as the least favourable option for the management of MSW as this has the highest GHG emissions potential, whereas the lowest emissions were achieved through the anaerobic digestion of sorted organic waste. Liu et al (2017) noted that in China, the MSW fraction contained a high organic fraction, which accounted for 60-70% of the total MWS fraction when compared to other developing countries. Therefore the GHG contributions from landfills are significant. However the study noted that the moisture content of the organic fraction was >50% in most small to medium cities which results in high leachate content and therefore be not be the most suitable feedstock for an incinerator. The outcome of the study identified that source separation of MSW with the anaerobic digestion of the organic fraction followed by the incineration of the inorganic fractions would result in the highest GHG emission reduction.

The Africa Waste Management Outlook states that, an average of only 55% of MSW is collected across the continent, the remaining waste being disposed of into open dumps, drains and rivers (Godfrey et al, 2019). The collected waste is either burned or disposed of into landfill facilities (Gautham & Agrawal, 2020). GHG emissions are released through various waste treatment methods, the largest source of which is the disposal of waste to landfill. Efforts to divert organic waste from landfills is seen as a significant means to reduce the climate change impact of municipal solid waste. However, waste management and governance in Africa has many gaps, these range from gaps in waste disposal to recycling which give rise to opportunities for technological innovations. However, the uptake of alternative waste treatment technologies in Africa has been slow, this is due to predominance of open burning and dumping of waste (Godfrey et al 2019). This results in difficulties in implementing conventional waste treatment technologies. Therefore, Godfrey et al 2019, proposes a combination of small scale, low-cost, decentralised initiative as well as larger scale, higher-cost centralised solutions. Although most African countries have a level of policies and measures that align with improving how waste should be managed, waste management in African countries are still constrained by various factors (Godfrey et al, 2019). One such major constraint identified is poor financing, this being the case as waste management in Africa is still viewed as a high risk investment (Godfrey et al, 2019). Policies and measures to address the GHG emissions from waste have been implemented globally, many of which focus on the diversion of food waste from landfill and the recycling of wood waste and garden refuse into other products.

In order to optimise how waste recovery and resource efficiency can contribute to climate change Corsten et al. (2013) postulates that aiming at high quality recycling can contribute to significant emissions reduction in the Netherlands. The study emphasises the successful recovery of materials in the Netherlands to be used as a resource and into waste to energy technologies such as anaerobic digestion and incineration. However, the study realises that existing policies only addresses part of the full potential of resource recovery and emissions reduction. Further measures and analysis are needed to implement a fully integrated waste management system that contributes to GHG emissions reduction.

The biological treatment of organic municipal solid waste is an established waste treatment technology across Europe and Asia, however in Africa particularly South Africa, it is only minutely recognised (Geben and Oelofse, 2009). The use of anaerobic digestion has been present in the South African context since the early 1990's for the management of organic

matter in sewage treatment plants (Greben and Oelofse, 2009). However, the failure of the plants operations can be linked to challenges in operation and the maintenance of the infrastructure the plants. Technological failures of anaerobic digestion systems, particularly in developing countries are of the linked to similar observations such as the education or skills levels of operators, maintenance of complex and expensive systems, technical and financial constraints as well as infrastructure requirements (Greben and Oelofse, 2009). An observation made in the study conducted by Greben and Oelofse (2009), states that the resource potential of organic waste in South Africa is dependant on factors such as an enabling governance environment.

According to Mohareb et al, 2011. there are various ways in which GHG emissions for waste can be quantified, the first is a methane commitment (MC) approach which looks at a theoretical gas yield or forecast of methane emissions that will be produced from municipal solid waste based on landfill operations. The second is a waste in place (WIP) method which attempts to calculate the methane emissions released within a year from all of the accumulated MSW disposed of into landfill. The more commonly used approach by is the methane commitment approach adopted by the US EPA in the Waste Reduction Model and the IPCC (Mohareb, 2011). The use of different methodologies to quantify GHG emissions with different parameters can be of use for the planning phase of waste management. This can allow for an assessment of scope 1 and scope 2 emissions.

Life cycle assessment methods are standardised internationally and is considered the most effective tool for the identification and assessment of environmental impacts linked to waste management (Cherubini et al., 2009). This encompasses a variety of technology options such as anaerobic digestion, composting and incineration. LCA studies are used for the development of waste management strategies and is dependent on the availability of waste data. Iqbal et al, 2020 states that the quality of input data is vital to the production of reliable results in LCA studies. A study conducted by Bandara et al. (2007) stipulates that understanding the composition and amount of waste generated is vital to the development of effective integrated waste management strategies. The study states that the amount of waste generated is proportional to the total population and average income (Bandara et al, 2007). However other socio-economic factors such as climate, living habits and social attitudes can influence waste generation. Another study conducted by Herinato et al, 2019, conducted a survey of the factors that influence waste generation in Palangka Raya City in Indonesia, determined that although

the environment and income levels influence waste generation within a 95% confidence level, the number of people per household influenced waste generation with a 99% confidence level. Further to this, a study conducted in China, utilised multiple statistical analysis and 12 parameters such as GDP, GDP per capita, urban population among others to determine what factors influence waste generation. The study determined that the relationship between GDP and MSW generation was not clear cut but rather this was more likely relevant to a developed country context than that of a developing country.

2.2 Municipal solid waste management best practices

Conceptually there has been a drive to shift municipal solid waste from a linear flow, the disposal of solid waste to landfill to the circular economy whereby MSW can be recycled or in resource recovery (Iqbal et al, 2020). In the shift towards a circular economy, the upper ranks of the waste hierarchy need to be incorporated through the prevention, reuse and recycling of materials. The circular economy trend is characterised by the effective use, reuse and minimisation of waste generated. This is through improving resource consumption, preserving the value of resources and ultimately waste minimisation (Adeleke et al, 2021). The circular economy is a synergy of the consumption of resources, generation of waste and emissions. In order for this to be achieved, a paradigm shift is needed to revamp the waste sector. Aligning with state-of-the-art solid waste management systems means transforming from collection and disposal to the application of the waste hierarchy which incorporates system design, material and energy recovery and wasted resources (Adeleke et al, 2021). Adeleke et al, 2021 suggests three levels at which the circular economy can be implemented into waste management, these are:

- a) At micro level through product reuse and recycling
- b) At meso level such as waste trade markets and renewable resources
- c) At macro scale through zero waste management strategies at regional levels

(Adeleke et al, 2021)

Life cycle assessment studies were developed to quantify the impacts of a product throughout its lifecycle, the aim of which, in waste management is to compare different waste treatment methods (Iqbal et al, 2020). LCA studies are used to identify best practice in municipal solid waste management which is crucial for policy makers to select optimal practice solutions. Iqbal et al .(2020) conducted a review of 75 LCA studies to evaluate the most appropriate waste

management technology with the best environmental performance. The study characterised integrated waste management as the amalgamation of two or more technology into the waste management system, the outcome of which was that the best case scenario for waste management is the use of two or more technology options whether or not incineration was included. The study suggests that the integration of landfilling with incineration with a biological treatment option and landfilling is considered best practice, followed by landfilling and AD and lastly mechanical biological treatment with landfilling (Iqbal et al, 2020). However, these high-end treatment technologies require large investments and skilled labour which may only be applicable to the developed country context.

Although, top-tier strategies from the waste hierarchy such as waste prevention, source separation and waste minimization approaches should be considered and prioritized as preferred methods for transitioning toward a circular economy, the collection and disposal of MSW is still the primary waste management method used in developing countries to date. Therefore the integrated waste management technologies considered for the purpose of this study are from the lower ranks of the waste hierarchy. These technology options address the management of general unsorted, untreated MSW from households.

2.3 Technologies related to the management of solid waste

a) Landfills

Although there is a shift in focus in many parts of the world on the need to rely less on landfills however, landfills to date, represents the dominant waste management solution in South Africa and the Africa continent. Basic elements of modern engineered landfills include a waste containment liner, which serves as a barrier to separate waste from surface environment. The disposal of waste to both engineered and non-engineered landfills involves the deposition of solid waste into excavated portions of land. Within South Africa, landfills are managed under the norms and standards for the disposal of waste to landfill which classifies landfills according to the waste types disposed at the facility (DEA, 2013). Engineered landfills are designed to reduce the impact of waste disposal on the environment through mechanisms such as lining of the landfill, compaction of the waste and covering.

b) Landfill with gas extraction

The disposal of municipal solid waste to landfill also results in the chemical and biological degradation and decomposition of organic waste fraction of municipal solid waste resulting in the production of leachate and gaseous emissions. The decomposition of waste occurs in two fold, the first is aerobically through bacteria and air, the second is anaerobically which occurs once the waste is covered. (Niskanen et al., 2013). This type of anaerobic decomposition leads to the creation of landfill gas. Landfill gas (LFG) consists of methane (CH₄), hydrogen (H₂), carbon dioxide (CO₂), Nitrogen (N₂) and Oxygen (O₂) (Reddy, 2017). Using a series of pipes underground, a vacuum effect is created which extracts the gas produced and transforms it into either electricity, fuel or is flared. Jaramillo and Matthews, 2005 states that landfills start to produce gas from the beginning of waste disposal into landfills, the generation of this gas can continue up to 30 years post the closure of the facility. A further study on landfill gas to energy states that landfill can produce gas for decades post closure of the landfill (Rajaram et al, 2011). Therefore the implementation of LFG recovery projects are long term investments with the potential for several decades of gas yields.

c) Material recovery facility

The recycling of municipal solid waste refers to reprocessing of materials such as paper, glass, plastics and metals into other materials for reuse. This is done through the extraction of the recyclable fractions via a material recovery facility (MRF). The typical model for South African material recovery facilities incorporates the dry-wet model, within which all MSW is sent to a MRF, the dry fractions such as plastics, glass and metal are extracted from the wet biogenic fraction (Trois and Simelane, 2010). The dry recyclables are bailed and sent to recycling whereas the wet fraction can be sent an anaerobic digestion facility or composting .

d) Anaerobic digestion

Anaerobic digestion (AD) is a widely accepted and used method and treatment of the organic fraction of municipal solid waste. AD involves a number of metabolic reactions which results in the production of biogas in the absence of oxygen. These processes are hydrolysis, acidogenesis and methanogenesis (Khalid et al, 2011). Anaerobic treatment of organic waste takes a longer time to achieve biostabilization than that of aerobic process, this is due to the anaerobic process being sensitive to high levels of ammonia. Organic waste fractions with a low nutrient content can be co-digested with a nutrient rich substrate to increase gas yields. This can also be a source of biogas to meet energy needs (Khalid et al 2011). According to Chayani et al, 2019, a small industrial scale digester has the ability to produce gas yield for up

to 15 years. Therefore the planning and implementation of biodigester projects need to be incorporated into long term strategies and plans both at industrial and municipal levels.

e) Composting

The composting process is highly valued in the management of solid waste due to its robustness and ability to obtain a product of value (Cerda et al, 2018). Composting is a process whereby materials biologically degrade in the presence of microorganisms. Composting can be used for the management of degradable food waste materials. The benefit of compost is that it has the ability to improve the quality and nutrient content of soil. Although composting is a safe method for the management of food waste some of the challenges that occur are linked to odour and GHG emissions (Ayilara et al, 2020). Furthermore the market value of compost is low which poses a challenge for large scale composting plants.

2.4 Status quo of waste management in South Africa

The waste management landscape in South Africa has come into the spotlight in recent years, despite a shift in focus from the disposal of waste to landfill to the application of the waste hierarchy, only 10% of the municipal solid waste in South Africa is recycled (Adeleke et al, 2021). However, despite the advancement in waste management systems, the South Africa, the country faces various challenges and shortcomings. Most developing countries follow a similar approach to the management of municipal solid waste, which is the adoption of the waste hierarchy into waste management practices which incorporates the entire value chain of waste (Chimuka and Ogola, 2015).

The achievement of optimal waste management targets, the efficient use of resources as well as the collection, disposal and treatment of solid waste has been a challenge in South Africa, this is owing to the interconnectedness of waste management systems which, if deficient in any aspect affects the performance of the overall system (Adeleke et al, 2021). Two key challenges to the uptake of South Africa's waste management system is the exhaustion of landfill airspace which is compounded with an increase in the overall population and therefore a surge in waste generated and the limited access to funding (Adeleke et al, 2021). This poses a strain on the South African waste management system as existing facilities and strategies are insufficient to accommodate these challenges (Adeleke et al, 2021). Other challenges which have hindered the progress of integrated waste management in South Africa include insufficient waste

collection services, illegal dumping, unlicensed facilities, deficient waste minimisation and recycling initiatives and unreliable waste data.

At a municipal level, according to the Constitution of South Africa, local municipal authorities are responsible for waste management service delivery. Although service delivery has improved in middle and high income areas, low income and rural areas are still inadequately serviced (Fakoya, 2014). Although levels of service differ according to the municipal type, poor institutional practices are the source of inefficient and ineffective waste collection systems. This is combined with poor financial management, poor equipment management and shortage of skilled staff (Fakoya, 2014).

2.5 South African governance structures

The governance structure is separated into three sub sectors, each with a specific role in the overall management of the country's administration. These are the national government, provincial government and local municipalities. According to the constitution of South Africa, the spheres of government are distinctive, interrelated and inter-dependant (South African Government, 2024).

- National government

The overarching national government in South Africa is responsible for law making and the setting of policies in the country. National government is separated into three branches, the legislature, the judiciary and the executive. At national level, the national assembly is elected for a term of five years, this may only be renewed once (South African Government, 2024).

- Provincial government

Provincial government is responsible for the oversight of healthcare, education and social development within the province (South African Government, 2024).

- Local municipalities

South African local government is responsible for the provision of basic services such as water, refuse removal and sanitation. Local municipalities are governed by the municipal finance management act and the municipal systems act (South African Government, 2024). Local municipalities are governed by the municipal systems act (MSA) which provides a framework

for the manner in which municipal powers and functions are exercised and performed as well as the and municipal finance management act (MFMA) which determines how municipalities income and expenditure are managed. In line with national government procedure, local governments are elected for a five year period, two years post national elections (South African Government, 2024).

The result of these systems are inconsistencies in long term planning for waste management and climate strategies due to the need to meet immediate targets of poverty eradication and food and water security.

2.6 Waste management legislative instruments in South Africa

The South African government has taken steps to develop legislative instruments to curb the impact of various sectors, including waste, on climate change. The purpose of these instruments, applicable to the waste sector, is to ensure appropriate management of municipal solid waste streams as well as to reduce the impacts of waste on global warming and the environment. The Constitution of the Republic of South Africa serves as the umbrella legislative instrument for the country, which underpins sustainable development at its core.

Section 24 of the Constitution *“promises everyone a right to an environment that is not harmful to their well-being and to have the environment protected, for the benefit of present and future generations, through reasonable legislative measures that prevent pollution and ecological degradation, promote conservation; and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development”*

Furthermore, the Constitution stipulates that waste collection and disposal is the function of a local municipality as per Schedule 5B *“Local government must provide waste management services, which include waste removal, storage and disposal services”*. Therefore, South African local municipalities are tasked by the Constitution of the Republic of South Africa, to provide basic waste collection and disposal services at household level. In addition municipalities are required to manage general waste landfills facilities within their jurisdiction. However, rapid urbanization and population growth, compounded with economic development has resulted in an increase in waste generation at household level. This has had a direct impact on the ability of the municipal solid waste management departments to provide basic waste collection services to meet the ever-growing demand.

According to the State of Waste Report (SoWR) (DEA, 2018) out of the 54.2 million tons of general waste produced, 65.2% was disposed of into landfills. Of the 54.2 million tons of general waste produced only 11% was diverted from landfills (DEA, 2018). The largest contributor to the general waste component is the organic waste fraction of 56.3% which incorporates fractions from the pulp, paper and sugar industries (DEA, 2018). The General Household Survey conducted in 2021 indicated an increase in municipal waste removal services from 58.8% in 2019 to 62,9% in 2021. The South African National Department of Forestry, Fisheries and Environment (DFFE) have reported key challenges faced by South African municipalities with respect to waste management, these are:

- “Littering and illegal dumping;
- Low levels of separation at source;
- Lack of infrastructure for recycling;
- Lack of a recycling culture;
- Backlogs in waste service delivery;
- Inconsistent waste collection;
- Pertinent challenges due to non-compliance to permit conditions;
- Burning in landfills;
- Lack of support and cooperation for service providers working with waste in some municipalities;
- Lack of education and awareness in some districts;
- Waste sector not prioritised in some municipal IDP and budgeting”

(NWMS, 2020)

For the waste sector in particular, some of the legislative instrument developed for the management of solid waste include the National Environmental Management: Waste Act, the National Waste Management strategy. The National Environmental Management: Waste Act Of 2008 (NEM:WA) is the blanket legislative instrument for waste management in South Africa. The NEM:WA defines waste as:

“‘Waste’ means—

- (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.”*

These definitions are of utmost importance to municipalities and businesses operating within the sector as this determines the applicability for the need of a waste licence.

The above definition of waste has been amended since the 2008 Waste Act was first promulgated. The Waste Act further defines what sources of waste are as well as the types of waste considered. In accordance with the Waste Amendment Act, 2014 (Act No 26 of 2014) various sources and types of waste exist. Much like the definition of waste being specified by legislation, so too are the sources of waste:

“Different types of waste may be generated from a variety of sources such as: Residential, Industrial, Commercial, Institutional, Construction and demolition, Municipal services, Process (manufacturing, etc.) and Agricultural activities.

Depending on the classification conducted in terms of the National Waste Classification and Management Regulations, Waste may either be classified as General or Hazardous”

The general waste stream includes and organic waste component along with glass, metal, paper plastics and other fractions. The Waste Act defines general waste as:

“means waste that does not pose an immediate hazard or threat to health or to the environment, and includes—

(a) domestic waste;

(b) building and demolition waste;

(c) business waste; and

(d) inert waste.”

Hazardous waste management is the function of national government, the DFFE is responsible for all hazardous waste landfill facilities. The Waste Act defines hazardous waste as: *“means any waste that contains organic or inorganic elements or compounds that may, owing to the inherent physical, chemical or toxicological characteristics of that waste, have a detrimental impact on health and the environment.”*

The National Waste Management Strategy (NWMS) is a legislative requirement of the Waste Act that gives effect to the application of the Waste Act. The main purpose of the NWMS is to aid in achieving the objectives set out in the Waste Act. In 2020 the NWMS was revised and updated following the 2011 NWMS. The updated NWMS has been developed to align not only with Sustainable Development Goals 2030 but also the National Development Plan: Vision 2030.

2.7 Integrated waste management models

In order to calculate the global warming potential and/or GHG emissions and emission reductions first order decay models are used. These models, contain various indicators, some of which have the potential to contribute to integrated waste management planning. Such models are aimed at supporting the decision-making process for the development of integrated waste management strategies and plans. These models however are heavily reliant on the availability of good quality data. This data forms the input data for the assessment of potential alternative waste treatment technologies which contribute to the mitigation of GHG emissions as well as landfill diversion.

Apart from the MPA tool, various models exist globally that are used to determine the environmental impacts of waste management activities. Commonly used methodologies for the development of waste management tools are, life cycle assessment (LCA), environmental

impact assessment (EIA) and sustainable/environmental technology assessment (SETA). Some of these models include but are not limited to the Waste Reduction Model (WARM), EASETECH, WRATE and the Waste to Resource Optimization and Scenario Evaluation Model (WROSE) which are discussed below.

The Waste Reduction Model (WARM) is a lifecycle based model which is used primarily for GHG emissions accounting, landfill management, methane emissions, long term carbon storage, avoided utility emissions and transport emissions (Heller and Keoleian, 2015). The waste streams that serve as input data of the model are, MSW, construction and demolition waste and e waste. Key outputs of the WARM are GHG emissions and emission reductions from activities such as source reduction, recycling, composting, anaerobic digestion, combustion and landfilling (U.S. EPA, 2016). WARM was developed by the United States, Environmental Protection Agency (US EPA) with the purpose of assisting solid waste managers, planners and organizations track and report GHG emissions and emissions reduction potential from several waste management practices (U.S. EPA 2016). The WARM is a freely accessible online model, designed for assisting officials in the waste sphere in understanding the environmental consequences of alternative waste management practices. GHG emissions is the only output of the WARM model. The WARM model does not take into consideration the biogenic CO₂ emissions as a contribution to global warming (Heller and Keoleian, 2015). (Trois *et al*, 2023)

The Environmental Assessment System for Environmental TECHNOlogies (EASETECH) is a life-cycle-assessment-based model developed by the Technical University of Denmark with the primary purpose performing LCAs on complex waste streams (DTU, 2017). EASETECH focuses the materials flow modelling, which incorporates a mix of materials at different fractions with different properties (Clavreul et al., 2014). EASETECH can be used for the analysis of emissions from the municipal solid waste fraction and therefore can be used to set up scenarios which calculate the emissions of a heterogeneous flow of materials (Clavreul et al., 2014). EASETECH was designed for a material flow analysis for the assessment of environmental technologies. The model explores a range of waste management activities such as source separation, collection, transportation, landfilling, LFG recovery, anaerobic digestion, recycling and composting (DUT, 2017). The output of EASETECH are environmental factors such as landfill airspace savings and GHG emissions reductions based on waste diversion volumes, stratospheric ozone depletion, human toxicity among others.

(Trois *et al*, 2023)

The Waste and Resource Assessment Tool for the Environment (WRATE) model was developed for the Environment Agency in the United Kingdom by Golder Associates. The WRATE model is a LCA model which focuses on environmental impacts of waste management activities throughout its life-cycle. WRATE assesses various types of environmental impacts of waste management activities such as climate change, acidification, aquatic ecotoxicity, human toxicity, resource depletion and eutrophication (Gentil, 2006). The waste streams considered in the WRATE model include MSW, commercial and industrial waste and builder rubble. WRATE was designed to ensure that complex environmental and waste information can be analysed and communicated to various stakeholders (Gentil, 2006). The model looks at waste treatment technologies such as waste collection and transportation, recycling, AD, incineration among others.

(Trois *et al*, 2023)

The WROSE model is a decision support methodology developed in South Africa by the University of KwaZulu-Natal (UKZN) in 2010 (Dell'Orto and Trois, 2022, Sameera Kissoon, 2018, Trois and Jagath, 2011). The WROSE model was developed for municipal officials looking to implement alternative integrated waste management strategies. The model considers GHG emission reduction as well as landfill airspace savings of various waste management activities (Trois and Jagath, 2011). The model uses South African data as well as locally developed emission factors that makes it relevant to a developing countries context. The model covers a range of waste management technology options such as landfilling, landfill gas extraction, recycling, anaerobic digestion and composting. In addition, the WROSE model covers basic capital and operating cost of the waste management activities listed above. The purpose of the WROSE model is to assist municipal officials in aligning with national legislation in order to achieve greenhouse gas emission reduction from waste management activities. This is done through the inclusion of four levels of sustainability, which are, environmental, social, economic and institutional to accomplish a fully integrated waste management system.

Within the WROSE model a specific set of scenarios are rooted, this ranges from a baseline or business as usual to more intricate optimised solutions. For this study 5 scenarios were considered. Figure 1 below is a graphical representation of the WROSE models scenarios

which can be adjusted in accordance with the requirements of the end user. The input data for the model is waste tonnages of specific streams. The outputs of the model include methane emissions and potential reductions achievable through the implementation of specific technology options. The outputs further include other indicators such as landfill airspace savings (LSS), economic indicators, job creation potential, the need for public participation, health risks, and institutional indicators such as applicable policy and legislation for the implementation of specific indicators (Trois *et al*, 2023).

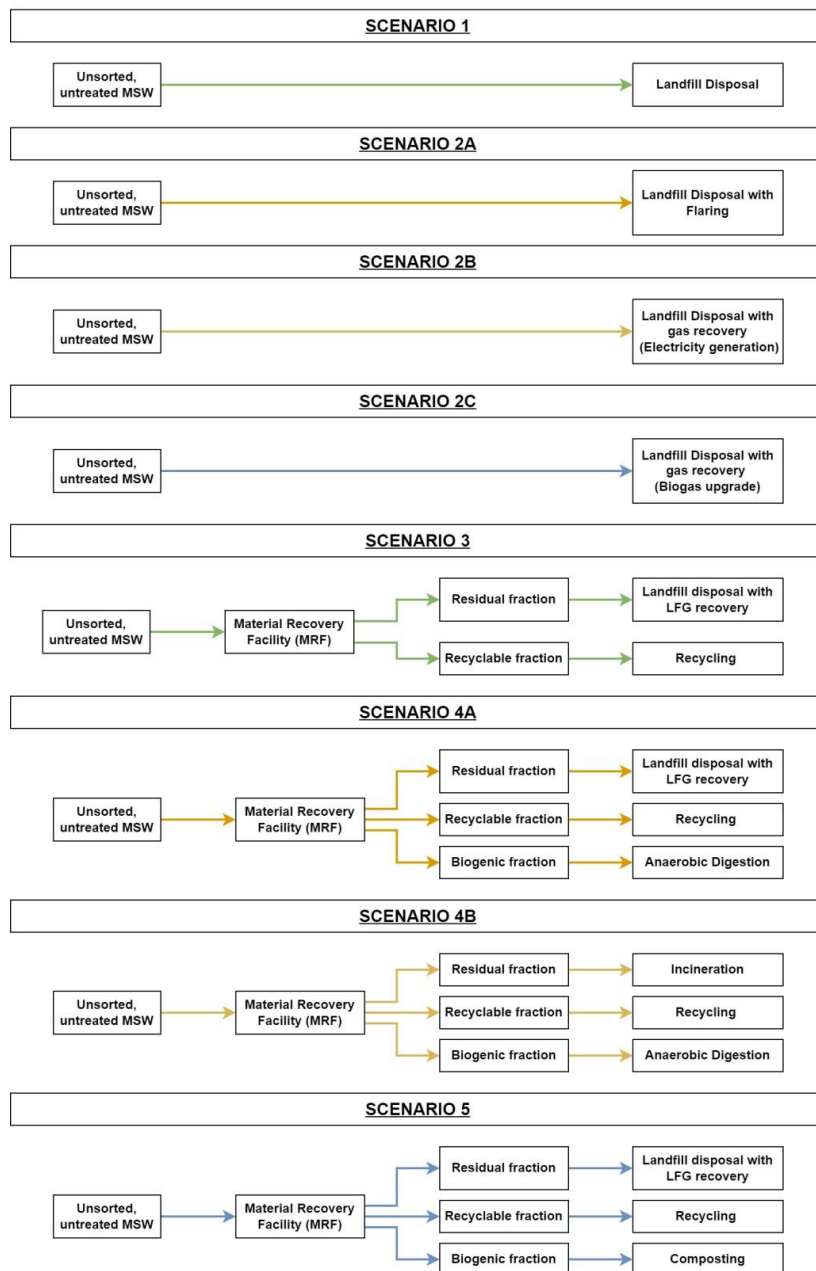


Figure 1. WROSE scenarios schematic (Dell'Orto and Trois, 2022, Trois and Jagath, 2011, Trois et al, 2023).

The WROSE model is an LCA based model which uses activity data as its input, this is in the form of waste quantities per scenario. Thereafter, the model generates outputs in the form of GHG emissions reduction in MTCO₂eq, potential landfill space savings and job creation potential. Although the WROSE model contains multiple scenarios and can output results for

a number of indicators, the model is still limited in its capabilities for long term GHG emissions projections and forecasting capabilities. For the purpose of this study, the Waste Resource Optimization and Scenario Evaluation (WROSE) model is used in two ways, namely the scenario selection and the advancement of the model to conduct long term projections of emissions from waste management activities.

2.8 Waste stream assessment

Table 1 below provides an example of the manner in which municipalities and national government characterise waste streams. This table was developed with data extracted from the integrated waste management plans of the Garden Route District Municipality, the City of Cape Town and State of Waste Report.

Table 1. Comparison of waste characterisation streams per municipality versus national State of Waste Report (SoWR, 2018; GIBB, 2018, CoCT IWMP, 2019)

Waste Fraction	State of Waste Report	Garden Route IWMP	City of Cape Town IWMP
News Paper			
General mixed paper	X	X	X
Scrap boxes and cardboard		X	
Low-density polyethylene (LDPE)			
High-density polyethylene (HDPE)			
Polyethylene-terephthalate (PET)			
Polypropylene (PP)			
Polyvinyl chloride (PVC)			
Polystyrene (PS)			
Glass	X	X	X
Steel cans/tins			
Aluminium cans			
Garden Waste		X	X
Biogenic Food waste		X	X
Garden Refuse: Green			
Garden Refuse: Wood		X	
Soft Plastics		X	
Hard Plastics		X	
Inert Waste		X	
Other	X	X	X

MSW	X		
Textile Waste		X	X
Nappies		X	
E-Waste		X	X
Commercial and Industrial Waste	X		
Construction and Demolition Waste	X		
Tyres	X		
Metals (mixed)	X	X	X
Plastics (mixed)	x		X

As seen in the table above, at national level, the waste streams are separated into nine fractions, whereas in the Garden Route District, 14 fractions were considered. The City of Cape Town also considered nine streams, however, these do not align with the fractions reported in the State of Waste Report. This brings to light one of the key gaps and challenges for GHG accounting at municipal level as GHG emission factors are developed according to waste types and technology selections. The aggregation of streams such as garden refuse, mixed metals or mixed plastics leaves room for various uncertainties and assumptions to be made.

2.9 Chapter Summary

This chapter presents the contextual background of the study by providing insight into global best practice in waste management as well as the status quo of waste management in the African context and South Africa. This review also assessed the challenges faced by South African Municipalities in shifting towards a more integrated waste management system some of which are limited financial and human resources. Furthermore, the establishment of integrated waste management infrastructure as long term investments, is hindered by short term electoral cycles and immediate needs such as poverty eradication. An assessment of existing waste management models was conducted, one of the key gaps identified is that none of the tools reviewed has the potential to conduct long term GHG emissions forecasting. The review also assessed the factors that contribute to how waste generation rates are determined, one key finding is that in developing country contexts population determined the amount of waste generated. Therefore, for the purpose of this study, the forecasting of MSW generation is kept proportional to the population in line with South Africa being a developing country.

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Chapter 3 - Methodology

This chapter presents the methodological approach adopted for this study. The overarching purpose of this study is to mainstream the concept of climate change modelling in waste management decision making. This is achieved through highlighting the importance of climate considerations in the waste management decision making process in efforts to contribute to meeting NDC targets. The aim of this study, therefore, is to develop an adaptable climate change mitigation strategy for South African municipalities, using the Garden Route District Municipality and the City of Cape Town as case study municipalities. The study aims to determine how climate mitigation can be achieved for the organic fraction of municipal solid waste. Given the research question proposed, a mixed methods investigative approach is used for this study.

3.1 Structure of Methodological Approach

The first step of this study was a systematic literature review which was used to conduct a gap analysis. The literature review incorporated a global overview of waste management practices, outlining how waste is managed in a developed and developing country context. The literature review also focused on waste management technologies, successes and failures. Further to this, a review of existing GHG models was proposed and it revealed a research gap since none of the models conduct emissions forecasting for long term planning of waste management activities.

The second phase of the study was to develop an algorithm for long term forecasting of GHG emissions to be incorporated into the WROSE model. Various studies conducted have determined that the amount of waste generated is proportional to the total population. Therefore, a linear regression methodology was used in the development of the algorithm for forecasting the waste quantities and population which served as input activity data for GHG emissions forecasting. This was done developing an Excel based platform for all of the identified technology options and scenarios of the WROSE model.

Two case study municipalities were selected for testing of the models additional forecasting capabilities. The outcome of which serves to feed into the development of a framework for a climate mitigation strategy which contributes to the overall goal of meeting NDC targets, these were the Garden Route District Municipality and the City of Cape Town Metropolitan Municipality.

In order to achieve the aims of this study, the WROSE model was applied. However, the WROSE model in its existing form does not contain forecasting capabilities in order to conduct long term GHG emissions predictions. Therefore, this chapter focuses on the advancement of the WROSE model to embed forecasting capabilities in order to conduct the study for long term climate stabilization from waste management activities.

3.2 Overview of waste management decision support tools

In the literature review component of the study, various waste management tools were reviewed. This review served as a gap analysis of the capabilities of these tools, the outcome of which was that, although each of the tools examined is strengthened by its own capabilities, none of the tools reviewed incorporates any long term forecasting capabilities. The table below summarises the findings of the review of each model.

Table 1: Summary of waste management decision support tools

Decision Support Tools	Environmental Indicators	Economic Indicators	Socio-Economic Indicators	Institutional Indicators	Long term GHG emissions forecasting capabilities
WARM	Yes	No	No	No	No
EASETECH	Yes	Yes	No	No	No
WRATE	Yes	No	No	No	No
WROSE	Yes	Yes	Yes	Yes	No

3.3 Existing WROSE model

The Waste Resource Optimisation and Scenario Evaluation Model is a decision support methodology developed with the goal of assisting South African Municipalities in achieving waste reduction and zero waste targets. The WROSE model, is an Excel based methodology which requires waste quantities as activity data inputs. Using locally developed emission factors, the model outputs GHG emissions and emission reduction potential from a range of waste management technology options ranging from landfilling to anaerobic digestion and

other waste treatment technologies. The WROSE model uses a scenario based approach to waste management, incorporating multiple potential options and technologies for the management of municipal solid waste. In the development of the WROSE model, the scenarios and technologies selected based on the most applicable options for the developing country context. These are:

The development of the WROSE model incorporated five technology options for the management of municipal solid waste. These technology options formed the basis for development of the scenarios which would be used for the assessment of environmental indicators for municipalities. The scenarios identified included current waste management practices in South Africa as well as alternative waste treatment technologies relevant to the South African context (Reddy, 2016).

The scenarios chosen for the evaluation are as follows:

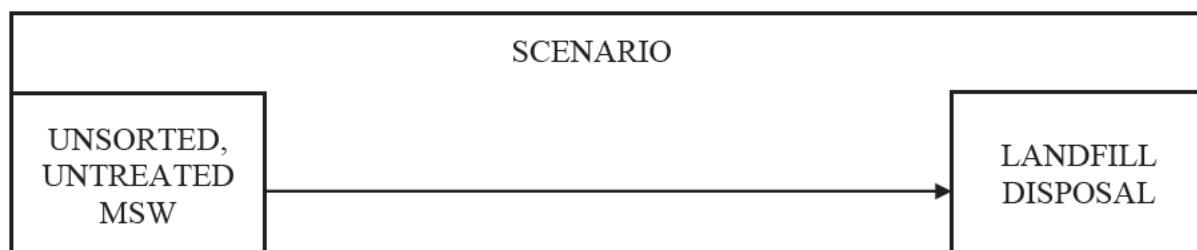


Figure 1: Scenario 1

Scenario 1 is viewed as a baseline scenario which evaluates the environmental implications of the disposal of unsorted, untreated MSW to landfill. The disposal of waste to landfill is to date the most utilised method of waste management across South Africa and the African continent.

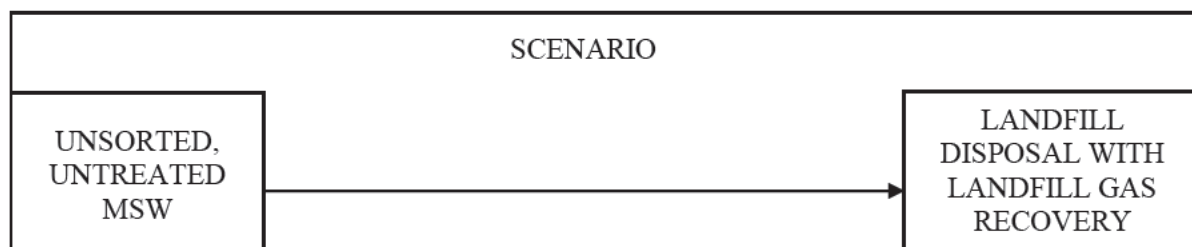


Figure 2: Scenario 2A

Scenario 2A evaluates the environmental implications of landfill disposal with landfill gas recovery and flaring on a municipality, this is through the disposal of unsorted, untreated MSW

into landfill with the extraction of landfill gas via a series of pipes which occurs from the decomposition of the organic waste fractions within a landfill facility.

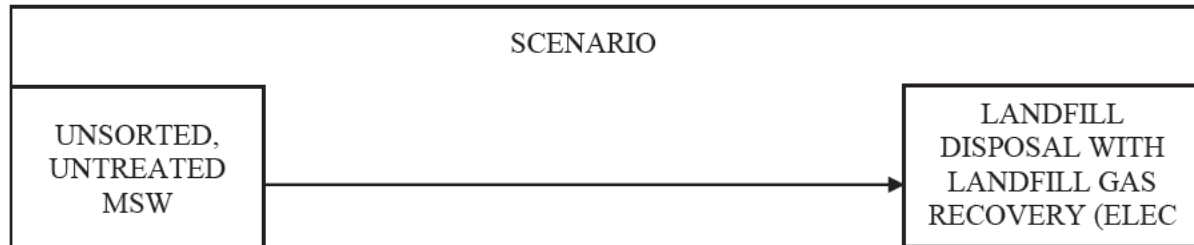


Figure 3: Scenario 2B

Scenario 2B is similar to that of scenario 2A which evaluates the environmental implications of landfill disposal with landfill gas recovery however this scenario looks at the generation of electricity from landfill gas extracted on a municipality.

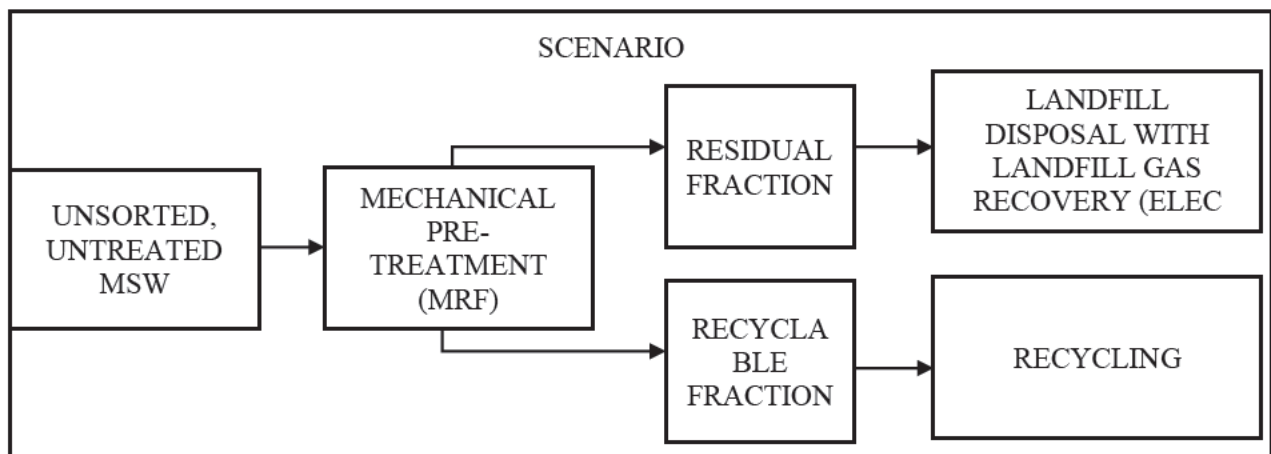


Figure 4: Scenario 3

Scenario 3 looks at the environmental implication of the implementation of a material recovery facility (MRF). Waste is sorted at the MRF separating the recyclable fraction from the residual that goes to landfill.

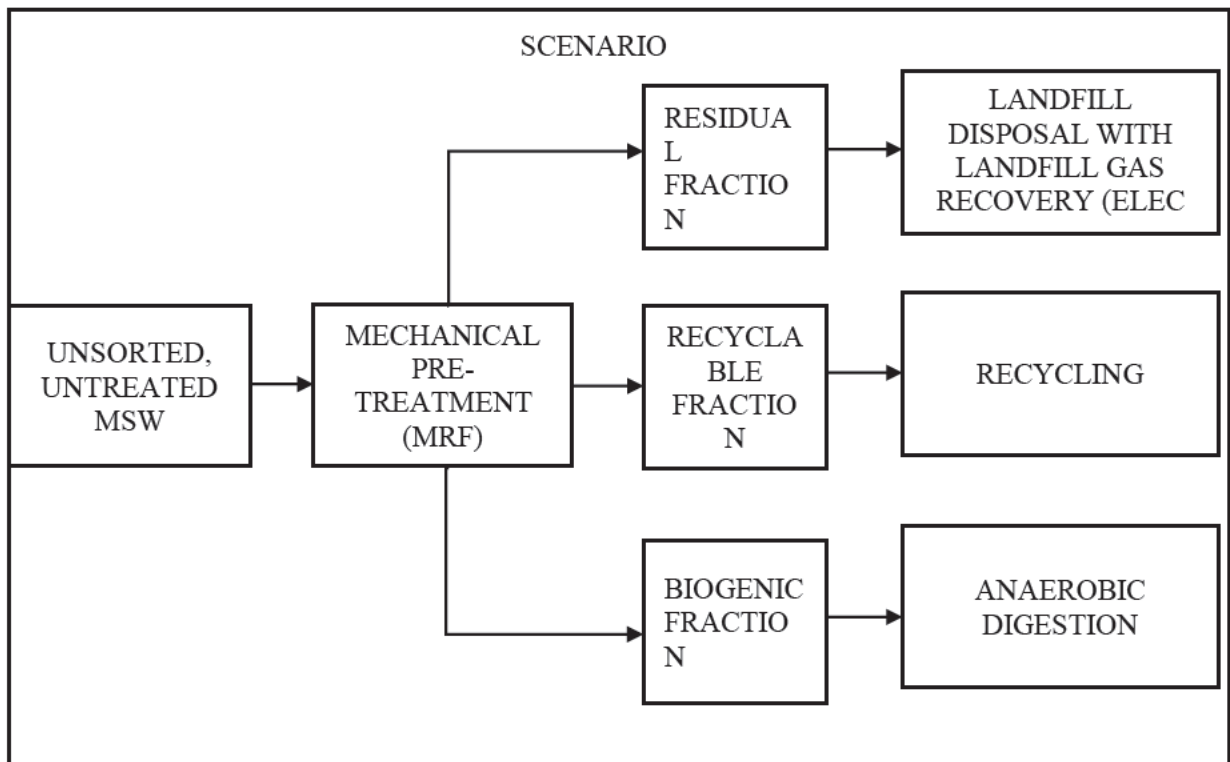


Figure 5: Scenario 4

Scenario 4 assess the environmental implications of the separation of unsorted waste via a MRF, where by the dry recyclable fractions are extracted for recycling and the biogenic fraction extracted for use in anaerobic digestion with the potential to produce electricity.

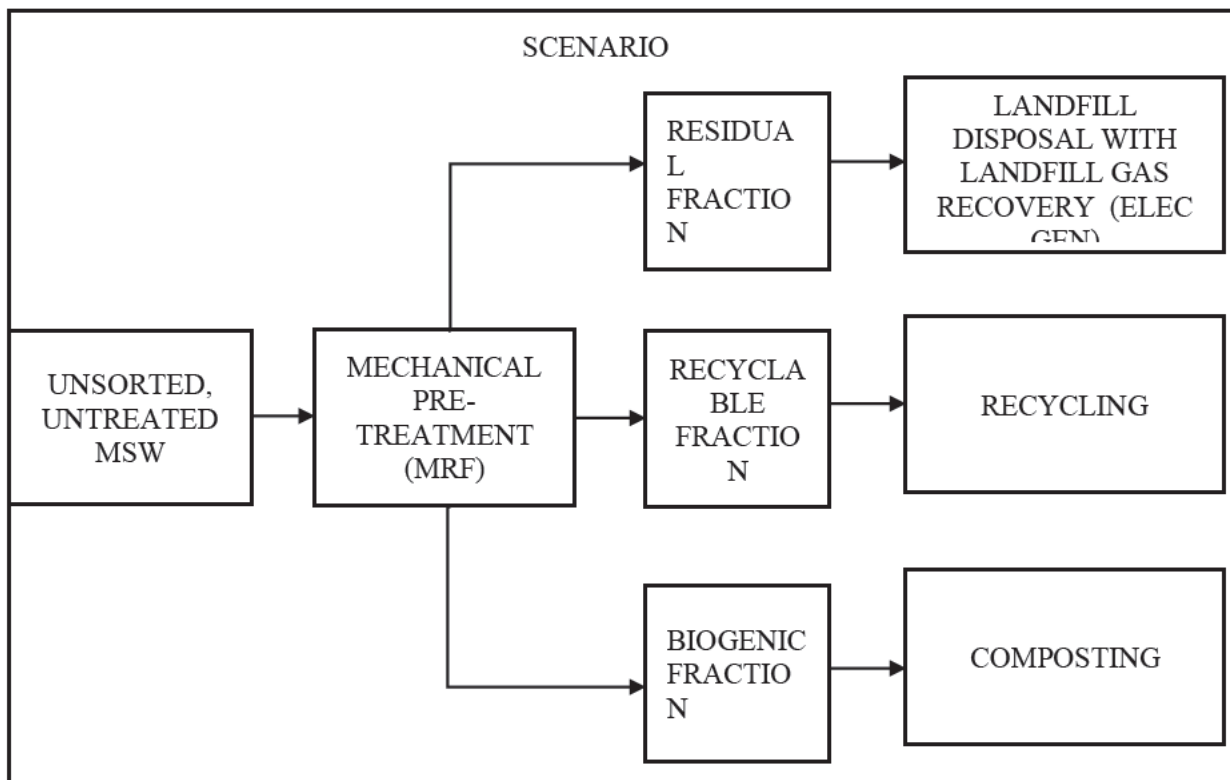


Figure 6: Scenario 5

Scenario 5 follows a similar process to that of scenario 4, whereby unsorted MSW is sent to a MRF and the dry recyclables are extracted. However, in this particular scenario, the biogenic fraction is used in aerobic composting.

The WROSE model has been further expanded to incorporate various indicators of sustainability. These indicators are the units of measure which form the outputs of the model. These include, environmental indicators, financial indicators, socio-economic indicators and institutional indicators.

- Environmental indicators

The environmental indicators embedded into the WROSE model include GHG emissions and emissions reduction potential, landfill space savings and waste diversion rates.

- Economic indicators

The WROSE model conducts basic economic assessments of each technology type. This includes capital and operational costs.

- Socio-economic indicators

The socio economic indicators of the WROSE model include job creation potential of each technology type, health risks and public participation.

- Institutional indicators

The institutional indicators incorporated into the WROSE model included environmental, energy and financial and administrative legislation that is applicable to each of the scenarios identified.

Using the indicators above the WROSE model the outputs are in the form of GHG emissions, landfill space saving, basic economic outputs such as CAPEX and OPEX of each waste treatment option, job creation potential, health risks and institutional indicators. The aim of this study however, is to mainstream the discourse of climate change on waste management decision making. Therefore the advancement of the WROSE model will focus on the GHG emissions component of the environmental indicators. Figure 7 below depicts the capabilities of the existing WROSE model outputs for GHG emissions from each scenario.

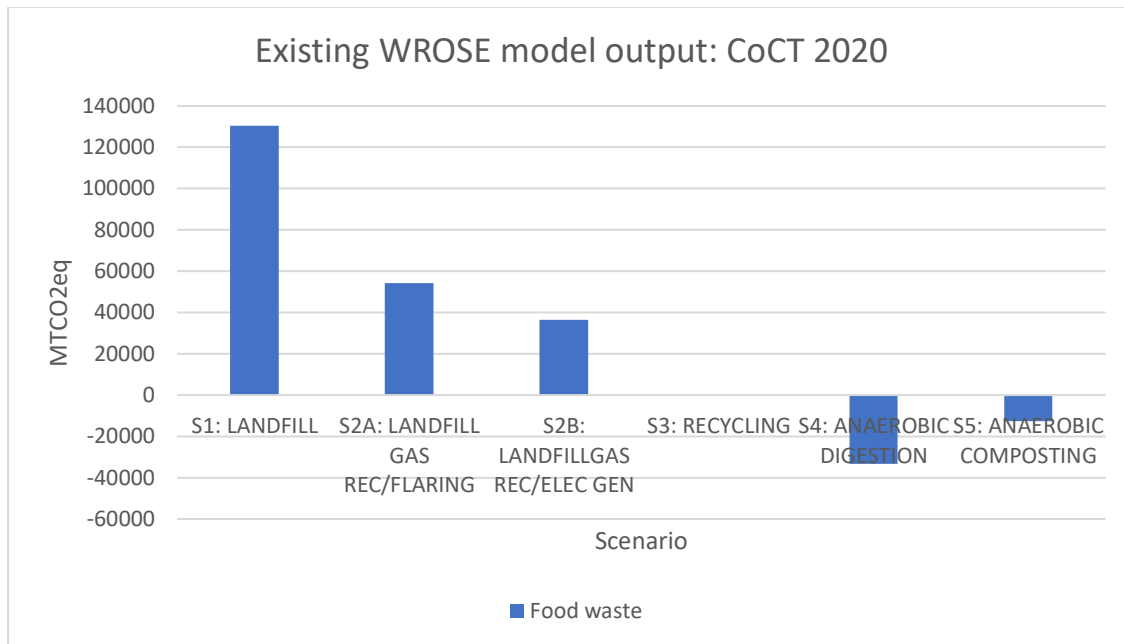


Figure 7: Example of existing WROSE model outputs for 2020

As seen in figure 7, emissions predictions are only estimated for the for the year in which the data is available. However, as mentioned in chapter 2, landfills, LFG recovery and AD have the ability to produce GHG's for decades post closure. Therefore this base year data is not suitable in its current form for long term planning for climate mitigation strategy development. Although the WROSE model is robust in its capabilities, the model faces some limitations in terms of long term predictive modelling of emissions and emissions reduction potential for long term waste management planning. Part of the limitation sit's with the fact that the WROSE model only outputs GHG emissions and emission reductions for the base year within which the activity data originates. Therefore there is a need to further advance the WROSE model with embedded forecasting capabilities that will allow for long term emissions mitigation planning.

3.4 Advancement of the WROSE model

In order to incorporate forecasting capabilities into the WROSE model, it is important to understand how to estimate long term population and waste generation rates. As mentioned in chapter 2, various studies have determined that waste generation is proportional to population to a 99% accuracy. Factors such as GDP were not incorporated due to its fluctuation and the income disparity in the developing country context. Therefore for the purpose of this study, population projections were used to determine long term waste generation figures.

Population and waste generations rates were determined based on historical available data. The equation below was used to determine a total population growth rate.

$$P_n = P_o \times (1 + r)^n \quad \text{Equation 1}$$

Where:

P_n = Estimated Final Population per year

P_o = Initial Population

r = Growth Rate (%)

n = number of years

Using the equation above, an average population growth of 2% per annum was established. In line with waste generation being proportional to population, a waste tonnage growth rate of 2% per annum was identified using Equation 2 below. This formed the baseline input data for GHG estimations for long term forecasting.

$$W_n = W_o \times (1 + r)^n \quad \text{Equation 2}$$

Where:

W_n = Estimated Final Waste Tonnage per year

W_o = Initial Waste Tonnage

r = Growth Rate (%)

n = number of years

Equation 3 represents the initial WROSE algorithm used to determine GHG emissions for a single year per technology option. In order to determine long term GHG emissions from the waste tonnages estimated using equation 2 above, the algorithm seen below in equation 4 was developed to determine long term GHG emission yields per scenario of WROSE model.

$$\text{GHG emissions for a single year } y \text{ (e.g year } y\text{):} \quad \text{Equation 3}$$

$$GHG_y = \sum_t (WA_y \times WF_i \times RR_t \times EF_t)$$

GHG emissions for the accumulated years (from 2013 to year y): Equation 4

$$AccGHG_y = \sum_{i=n}^y \sum_t (WA_y \times WF_i \times RR_t \times EF_t)$$

Where:

- **GHG_y** represents the greenhouse gas emission for year y.
- **AccGHG_y** represents the accumulated Greenhouse gas emission from initial year n to year y.
- **n** represents the initial year
- **t** represents the different waste management technologies.
- **WA_y** represents the amount of waste for the year y.
- **WF_i**, represents the percentage of waste fraction for i waste type.
- **i** represents the waste type (e.g., organic, plastics, paper, etc.).
- **RR_t**, represents the recovery rate for technology t.
- **EF_t**, represents the GHG emission factor for technology t.

Inputting the above algorithm seen in equation 4 into the WROSE model, allows the model to conduct long term forecasting of emissions and the potential long term emissions reduction. This advancement in the WROSE model will enable the user to gain understanding of GHG emissions and climate implications of waste management technology options for long term planning. Figure 3.8 below depicts the advanced WROSE model output with long term forecasting of GHG emissions and emissions reduction potential from four of the scenarios in the WROSE model.

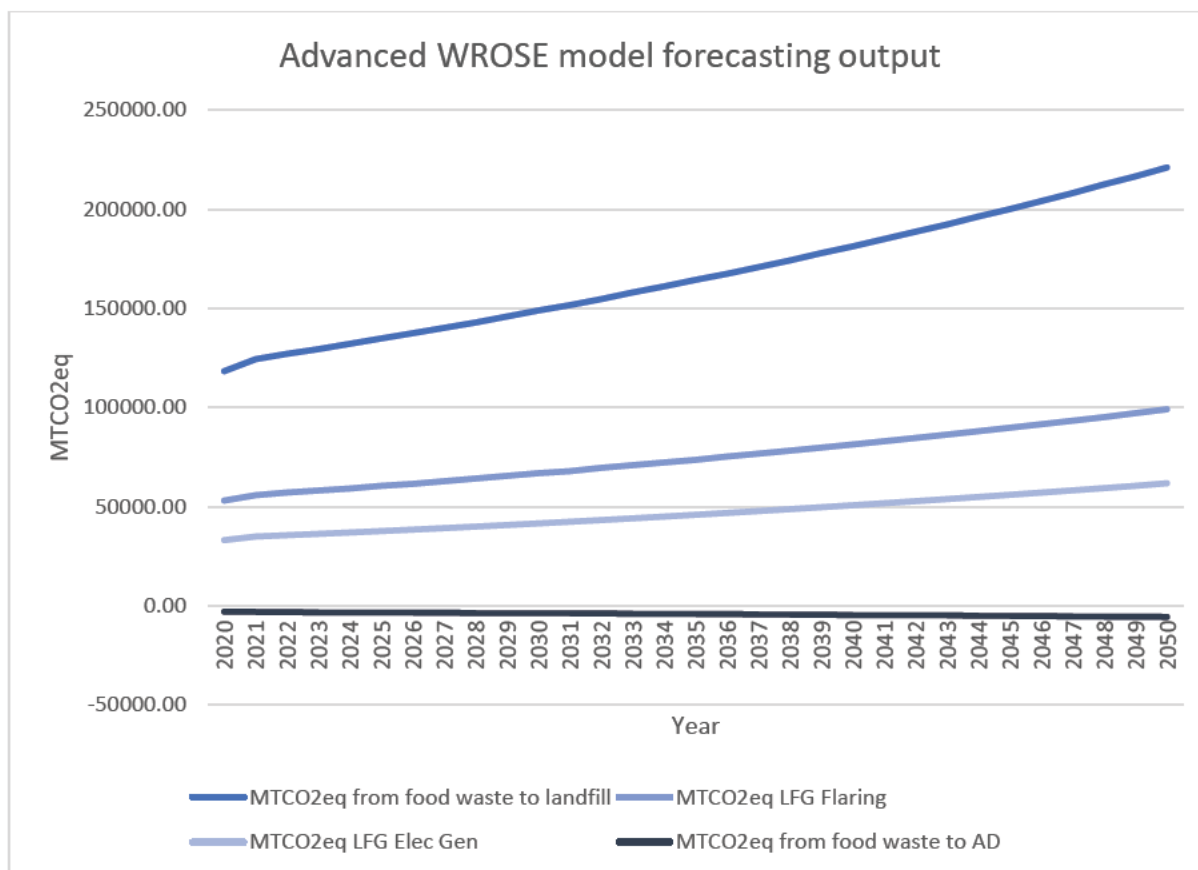


Figure 8: Example of advanced WROSE model outputs for long term forecasting per scenario

As seen in figure 8, the advanced WROSE model allows for long term forecasting of GHG emissions from various technology options. The purpose of this type of outcome allows for the long term planning of alternative technology options for organic waste fractions in efforts to reduce the impacts of organic waste on climate change. This information feeds directly into the development of a climate mitigation framework for organic waste.

3.5 Climate mitigation strategy framework development

In order to develop a framework for a climate mitigation strategy (Cohen et al, 2018) proposes the use of a multi criteria decisions analysis (MCDA) process, the use of MCDA incorporates the different goals of various role players to achieve one key objective (Cohen et al, 2018). One advantage of the use of MCDA is that it allows for the integration of qualitative criteria into the decision making process. However, MCDA come with certain constraints when developing decision making in the climate space. These are:

- a. Ranking and prioritization of individual mitigation and development actions against multiple criteria,

- b. Construction of portfolios of actions to form coherent strategic plans
 - c. Assessment of performance of such action portfolios against different criteria.
- (Cohen et al, 2018)

Figure 9 below is an example of a MCDA process value tree for the development of a climate mitigation strategy.

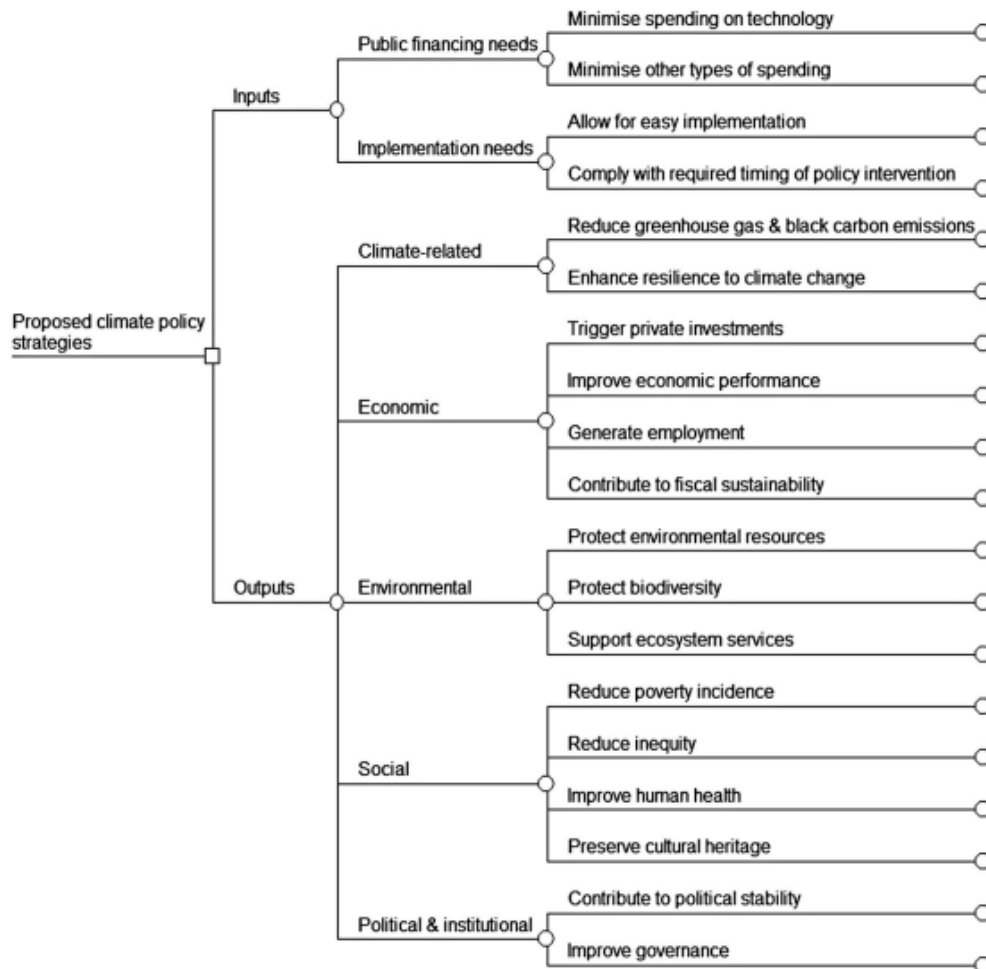


Figure 9. Example of a value tree for a climate mitigation co-benefits MCDA process (Cohen et al, 2018)

For the development of a decision making criteria using MCDA, it is worth noting that development of such a criteria is dependent on various factors. Boston (2008) noted that in the development of any criteria, several contextual matters are to be taken into consideration.

1. The criteria will vary based on national circumstances

2. The list of criteria can be controversial based on the users views on how it should be stated, interpreted and how it should be applied.
3. Particularly in democratic countries, the nature of short term electoral interests prevail over long term considerations (Boston, 2008)

For the purpose of this study, aspects of a MCDA will be used for the development of a framework based on the criteria identified in the table below. The criteria identified in the table below was extracted from a study directed at the development of a long term climate mitigation strategy (Boston, 2008), although extensive, the criteria incorporates all the necessary factors to consider in the development of a framework for a climate mitigation strategy for South African municipalities. This criteria has been applied to the development of a climate mitigation strategy specifically from the management of organic waste.

Table 2 Criteria for developing a climate mitigation strategy (Boston, 2008)

Criteria for development of climate mitigation strategy	
1. The framework should reflect the best available scientific evidence on the nature, scale and timing of the problems posed by climate change and the kind of stabilization targets to minimize risk of large-scale, highly damaging or irreversible changes to key biophysical systems.	(Boston, 2008)
2. The framework should recognize the need for a fair sharing of the burden of adjustment, both between nations and at the domestic level	
3. Economy-wide, as well as any sector-specific, emission-reduction targets (whether short to-medium term or long-term in nature) should be consistent with the primary objective of the UNFCCC	
4. The framework should recognize the need for effective measures to address both mitigation and adaptation.	
5. In relation to mitigation, the framework should take proper account of the critical features of the challenge. These include: a) the lengthy lags in the climate system; b) the high degree of path dependence generated by the long-term nature of investments in physical infrastructure and capital stock; and c) the fact that in pursuing any agreed stabilization target what matters is not the level (or precise flow) of emissions at any given point in time, but the total cumulative emissions over an extended period of time (and hence the stock of greenhouse gases in the atmosphere).	
6. The framework should recognize the need for integrated, collaborative global action and enable the country to meet its international obligations, e.g. binding emission-reduction targets or contributions to bilateral or multilateral initiatives.	

<p>7. The framework should balance the requirement for predictability and flexibility: predictability so that businesses, households and individuals can invest with confidence in a low-carbon economy and plan for the behavioural and structural changes required;</p>	
<p>8. In relation to specific policy initiatives, the framework should provide an integrated package of both market and non-market mechanisms, designed to maximize environmental effectiveness and economic efficiency</p>	
<p>9. The framework should provide institutional mechanisms required to facilitate and encourage a rapid transition to a low-carbon economy, including: a) well-resourced, high- . quality, independent advice to the government on critical policy-design and scientific issues</p>	
<p>10. The framework should ensure that progress towards achieving the agreed goals and targets is periodically assessed and properly reported, and that the government is fully accountable for the design, implementation and effectiveness of the measures taken.</p>	

The criteria defined in the table above served as a guideline for the development of the framework for the climate mitigation strategy .

3.6 Chapter Summary

The methodology used in this study incorporates both quantitative and qualitative approaches. A quantitative approach was used for the development of the algorithm for forecasting GHG emissions which was embedded into the WROSE model for its advancement. A qualitative approach was used for defining the criteria that was used to develop the framework for the climate mitigation strategy. The advanced WROSE model will be applied in 2 case study municipalities in chapters 3 and 4. Chapter 5 will look at how these outcomes translate into the development of the framework for a climate mitigation strategy for organic waste management.

3.7 References

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Chapter 4

OPTIMISED ORGANIC WASTE MANAGEMENT STRATEGIES FOR SUSTAINED CARBON EMISSIONS REDUCTION AND CLIMATE CHANGE STABILISATION IN THE GARDEN ROUTE DISTRICT OF SOUTH AFRICA

This chapter has been published as:

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The published paper is presented in the following pages

4.1 Abstract

The mitigation of greenhouse gas (GHG) emissions from the waste sector, particularly from landfilled waste and their impacts on climate change have been at the forefront of environmental management in recent years. However, as over 80% of waste is still deposited in landfills in South Africa, unsorted, there is therefore a need to design mitigation strategies that would synergistically achieve waste diversion and carbon emissions reduction. This study focused on the waste sector in the Garden Route District of South Africa, which is under pressure by the Provincial Government of the Western Cape to divert all organic waste from entering landfills by 2027. The research presents a detailed methane emission mitigation and climate change stabilisation strategy developed through the application of the Waste to Resource Optimisation and Scenario Evaluation model (WROSE), that employs the Intergovernmental Panel for Climate Change's (IPCC) carbon emission factors. Currently, more than 80% of the organic waste fraction is disposed of into landfill facilities across the district, resulting in continued production of GHGs into the atmosphere. The WROSE model compares the emissions from the current landfill disposal (Business as usual – BAU) with other more optimised scenarios including aerobic composting and anaerobic digestion, to identify the most suitable waste diversion and carbon emission mitigation strategy. The analysis shows how integrated waste management solutions can drive the circular economy and be employed

on a scenario basis to extract the organic fraction from disposal into landfill and contribute to sustained climate change stabilisation over the next 50 years. The outcome of the BAU scenario determined that methane emissions from landfills in the Garden Route District Municipality over the next 50 years would increase by almost three times the current emission rate if no other optimised interventions were put in place. The outcome of the study stresses the need for activating the circular economy through interventions to manage organic waste fractions and assist municipalities in long term policy and economic planning.

4.2 Introduction

Within South Africa, 80% of municipal solid waste is disposed of into landfill, the disposal of organic waste to landfill contributes approximately 4.3% towards the country's total GHG emissions (Oelofse, 2014). Waste management in South Africa is an emerging sector with increasing emphasis placed on the development and application of integrated waste management strategies through the waste hierarchy via the National Environmental Management: Waste Act - NEM:WA (DEA, 2009) and the National Waste Management Strategy – NWMS (DEA, 2011). The South African Department of Forestry, Fisheries and Environment (DFFE) conducted a Mitigation Potential Analysis (MPA) in 2014 which focused on GHG mitigation options in various economic sectors (DEA, 2014). The focus of this study aligns with the MPA conducted by the DFFE through the assessment of mitigation pathways in the waste sector (DEA, 2014). The aim of which is to develop scenario appropriate waste management strategies. The technologies assessed and strategies identified in this study contributes to the diversion of waste from landfill for the reduction of methane emissions and subsequently the production of new products. This will ultimately activate better waste to resource management and contribute to the circular economy. The circular economy is one potential driver of sustainable development, this can be achieved through the shift of the flow of materials from a linear flow or disposal to landfill to a circular flow through the identification of alternative uses to extract materials through the pipeline prior to the disposal of materials to landfill (Korhonen et al., 2018). The drive towards a circular economy is steered by the collective efforts both governmentally and in the private sector. This is through the transition from integrated and industry waste management planning mechanisms to the introduction and implementation of extended producer responsibility (EPR) mechanisms such as the draft EPR regulations of the NEM:WA gazetted in 2020 (DEA, 2009). This addresses the issue of the producers' responsibility in a post-consumer phase of a products life cycle.

Over the last two decades, the Western Cape, one of the largest provinces in South Africa, has focused its efforts on establishing itself as the “green hub” of Africa. The Western Cape houses 1 metropolitan municipality (City of Cape Town), 5 districts and 24 local municipalities. Amongst these municipalities is the Garden Route District Municipality (GRDM). The GRDM, with its 7 local municipalities, faces a pressing issue of limited landfill airspace. Furthermore, the Western Cape Provincial Government has issued a ban, which stipulates zero organics to landfill by 2027 with a halfway target of 50% reduction of organics to landfill by 2022. Therefore, all municipalities within the Western Cape are mandated to find alternative waste management solutions for food and organic waste fractions (DEA&DP, 2022). Within South Africa, waste management policies and legislations are gearing towards a low carbon economy. The Western Cape is amongst those transitioning towards a decarbonised economy.

The development and application of integrated waste management systems and ERP regulations aim to assist municipalities and the private sector in reducing the volume of waste disposed of into landfill facilities. For the purpose of this study, this is achieved through the advancement of the “Waste to Resource” economy using methane emissions as an indicator for the development of integrated waste management plans, thus reducing waste disposal to landfill. This serves as a driver in the development of a climate change stabilisation wedge for the activation of the circular economy.

The climate change stabilisation wedge is a concept introduced by Pacala and Sacolow in 2004. In recent years, the growing belief that methane emissions can be stabilized through the introduction of integrated waste management mechanisms has gained traction with various studies conducted globally. This is due to the complexity of waste management systems that differ from geography, policy, capital and operational costs amongst others (Bahor and Van Brunt, 2009). A stabilisation wedge (or triangle) is the triangle formed by the comparative analysis of the 50-year trajectory of methane emissions from the disposal of waste to landfill as business as usual, and those reduced from another more optimised scenario. Stabilisation is achieved by the flattening the trajectory through the introduction of interventions.

The aim of this study is to create a climate change stabilisation wedge/strategy for the GRDM by determining the effect on methane emissions, over a 50-year period and the potential to replace the BAU scenario with more optimised scenarios that maximise diversion of organic

waste from landfills. In this study, a multicriteria methodology is utilised through the integration of the WROSE model into the mitigation potential strategy for South Africa and identify scenarios to achieve the highest mitigation potential. The WROSE model (Trois and Jagath, 2011) is utilised to create a climate change stabilisation wedge (triangle) for each scenario. The climate change stabilisation wedge/triangle forecasts, over a 50-year period, the volume of methane emissions (estimated in metric tons of CO₂eq) that would be offset if landfilling were to be progressively replaced by alternative, more optimised, scenarios for food waste and garden refuse streams. Methane emissions for the WROSE scenarios evaluated are calculated using emission factors and methodology derived by the 2006 IPCC guidelines (IPCC, 2006).

4.3 Study Area

The GRDM, formerly known as the Eden District Municipality, was selected as the study area. The GRDM is the third largest district in the Western Cape covering 23331 km² in surface area (Gibb, 2020). The total population of the GRDM is at 635600 as per the 2020 integrated waste management plan (Gibb, 2020). The GRDM conducted an in-depth waste stream analysis in 2019 to determine the household solid waste stream profile across the district which was communicated in the Engineering 3rd Generation IWMP (Gibb, 2020). The outcome of which determined that recyclables including hard and soft plastic, paper, cardboard, metal and glass accounted for 40.3% of the total waste fraction. The total organic waste fraction accounted for 35.6% which included both food waste and garden refuse. The remaining 24.1% included textiles, nappies, e waste, hazardous waste and other. Figure 1 below depicts the waste generation percentages per fraction which is the basis for all of the analysis conducted. As seen in Figure 1, the food waste fraction is the largest fraction disposed of into landfill. Garden refuse is a second organic waste fraction that is taken into account for the purpose of this study and therefore a combined organic waste fraction of 35.6% is considered for the study.

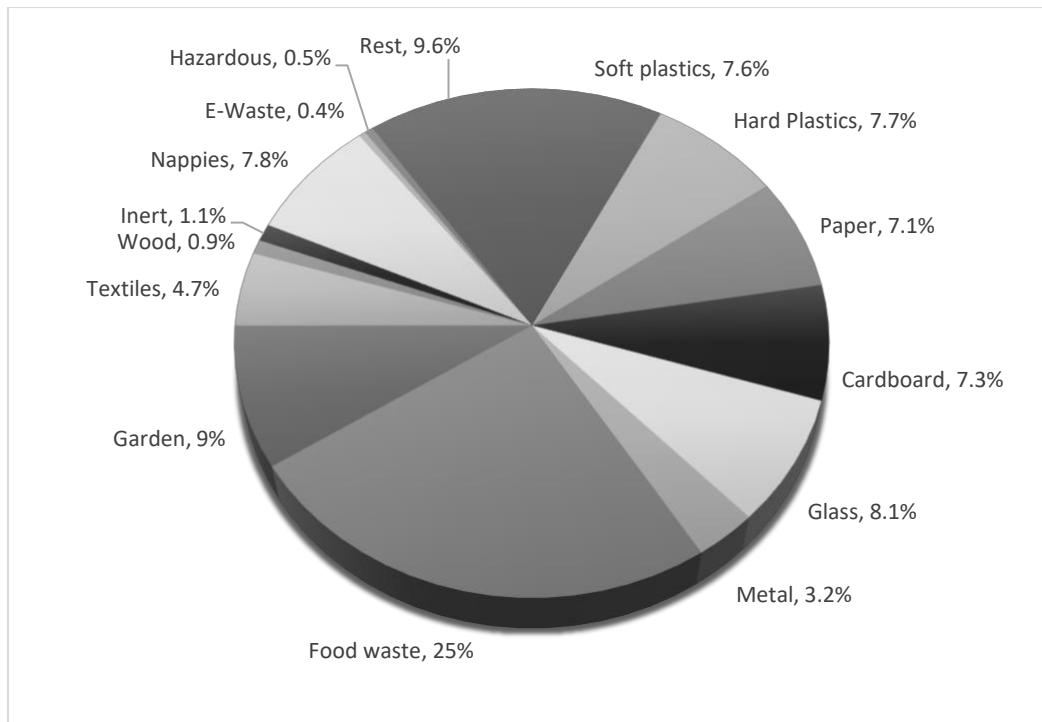


Figure 1: Average domestic waste profile in the Garden Route District Municipality (Gibb, 2020).

The Oudtshoorn, Kannaland and Hessequa Local Municipalities house their own local landfill facilities and will continue to utilise these sites for the disposal of their general MSW. Whereas, Mossel Bay, Bitou, Knysna and George Municipalities currently have no operational landfill facilities accepting general MSW.

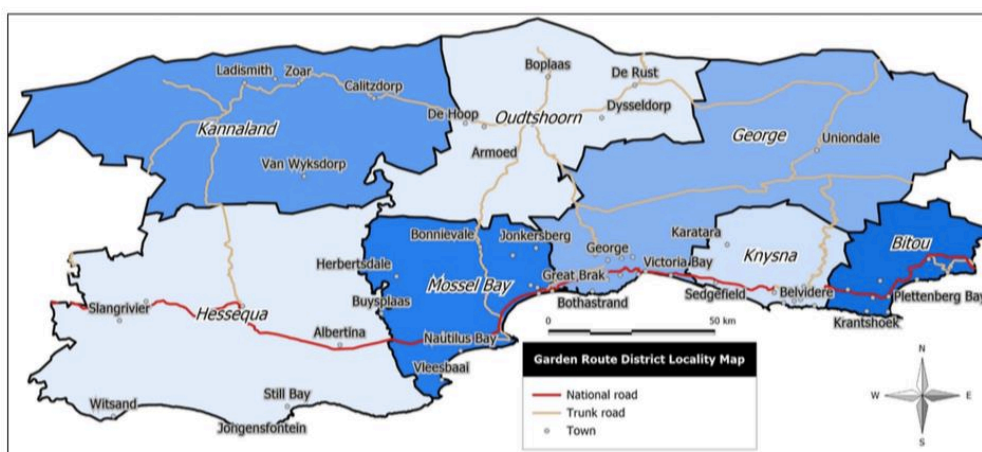


Figure 2: Garden Route district municipality, South Africa (Source: <https://municipalities.co.za/map/145/garden-route-district-municipality>).

All of the MSW collected is disposed of into the PetroSA sanitary landfill facility within Mossel Bay Local Municipality. The PetroSA site faces the pressure of limited landfill airspace and reduced life span of the facility. The GRDM is currently in the process of developing a new regional landfill facility due to the closure of the pre-existing facility which has now reached its maximum capacity in order to accommodate the waste volumes generated by the four municipalities. The GRDM has undergone a public private partnership (PPP) process for the construction, development and operation of a new regional landfill facility which will service four of the seven local municipalities in the district (Gibb, 2020). The facility will include a material recovery facility (MRF), a composting facility, a construction and demolition waste recycling facility (Gibb, 2020). The GRDM along with four local municipalities have undertaken a pilot home composting program in efforts to manage the organic waste fractions to meet the requirements of the Western Cape Provincial Government (Gibb, 2020).

4.4 Methodology

The methodological approach used in this study employs a combination of steps to achieve a climate change stabilisation wedge. Due to a lack of reliable, available data, specific boundary conditions needed to be assigned in order to achieve the aim of the study:

1. Historical Integrated Waste Management Plan (IWMP) and Integrated Development Plan (IDP) data was extracted and utilized for the forecasting of total population and waste generation figures;
2. Population growth was established at 2% per annum based on the projections conducted by the Department of Social Development in the Garden Route District Municipality in line with the district;
3. Average waste characterisation percentages were extracted from the 3rd generation IWMP for determining waste fractions in tons.

The first step in this study was the waste characterization conducted by the GRDM. The data collected during the waste stream analysis fed directly into step two, the scenario identification. The second step in the process is the waste strategy scenarios identification and selection. This was achieved through the use of the WROSE model (Trois and Jagath, 2011).

The Waste Resource Optimisation and Scenario Evaluation (WROSE) model is a methodology developed by the University of KwaZulu-Natal to aid municipalities in the decision-making process as a zero waste and GHG emissions reduction model (Trois and Jagath, 2011). The WROSE model is used to assist municipalities in aligning with national legislative requirements and achieving sustained waste and emissions reduction through the evaluation of integrated waste management scenarios upon all levels of sustainability (environmental, economic, social and institutional).

A number of scenarios are embedded in the WROSE model, ranging from baseline (business as usual) to more complex optimised solutions (Figure 2). For this study 5 scenarios were considered:

1. The disposal of unsorted, untreated MSW to landfill (BAU)
2. The disposal of unsorted, untreated MSW to landfill with landfill gas recovery and electricity generation (BAU+)
3. Unsorted and untreated MSW undergo a mechanical pre-treatment with recovery of recyclable fraction through a Material Recovery Facility (MRF)
4. Unsorted and untreated MSW undergo a mechanical pre-treatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with anaerobic digestion of biogenic food waste.
5. Unsorted and untreated MSW undergo a mechanical pre-treatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with composting of biogenic food waste (Trois and Jagath, 2011).

Figure 3 below outlines the scenarios of the WROSE model graphically. The WROSE model uses waste tonnages of each waste fraction generated as input data, the outputs of the model are methane emissions productions or reductions. The outputs of the model are not limited to methane emissions but rather expand to a range of indicators such as landfill airspace savings (LSS), economic indicators, job creation potential, health risks associated with the jobs created, and institutional indicators.

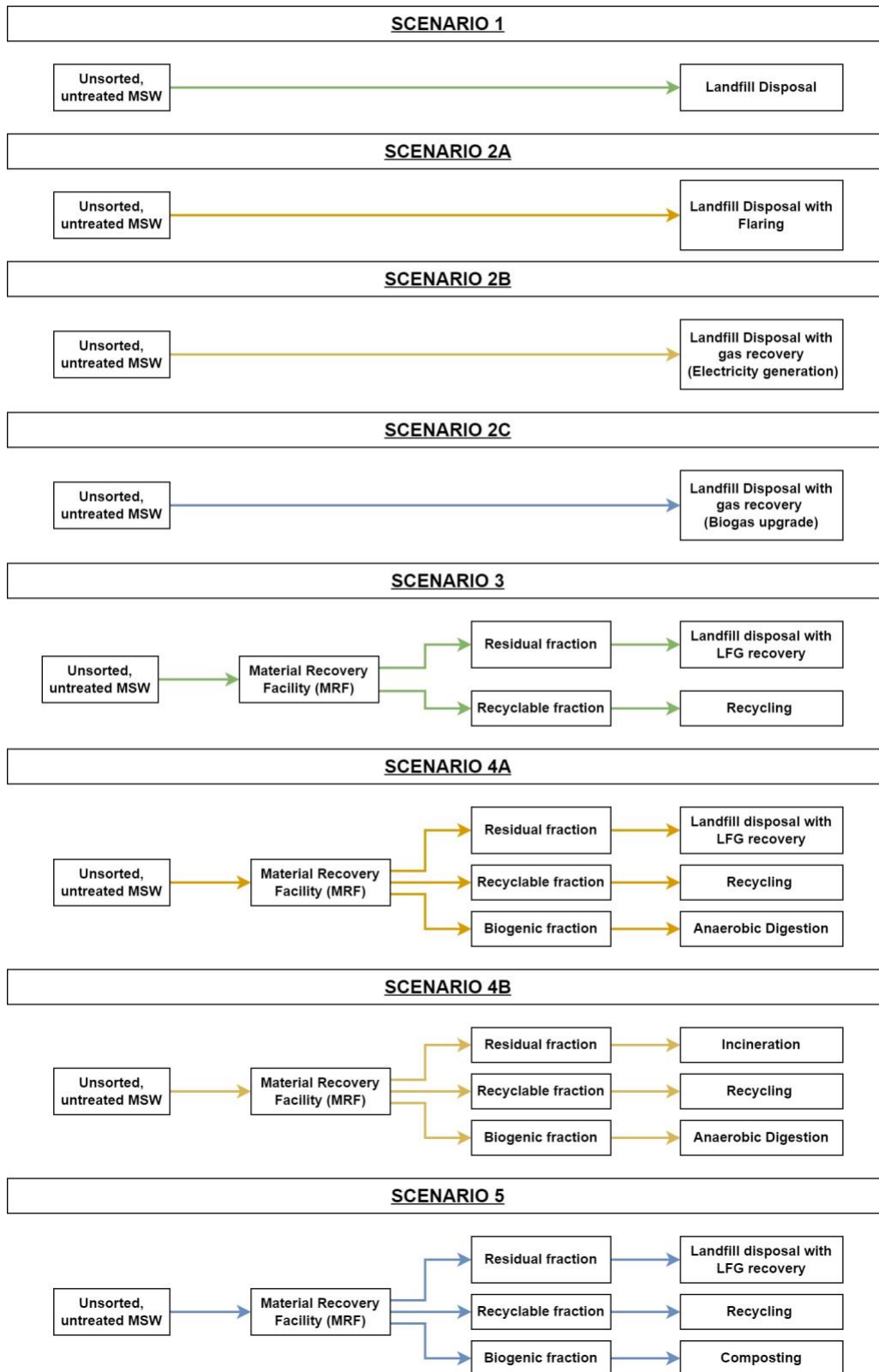


Figure 3. WROSE scenarios schematic (Trois and Jagath, 2011; Dell’Orto and Trois, 2022).

For the purpose of this study, the WROSE model was utilised for the selection of the scenarios that were assessed. Due to organic waste management forming the core focus area of the study, the scenarios identified as most applicable to this study are:

1. SCENARIO 1 - The disposal of unsorted, untreated MSW to landfill (BAU)
2. SCENARIO 4 - Unsorted and untreated MSW undergo a mechanical pre-treatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with anaerobic digestion of biogenic food waste.
3. SCENARIO 5 - Unsorted and untreated MSW undergo a mechanical pre-treatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with composting of biogenic food waste.

Historical census population data was extracted from the first, second and third generation IWMP documents of the GRDM, previously called the Eden District Municipality, to determine the population growth rate annually and to conduct forward projections (Gibb, 2020). From equation 1 below, a population growth rate of $r = 2\%$ per year was identified as per the increase in population figures extracted from Table 1 for the years 2013 to 2018.

Table 2. Historical population and waste tonnages figures (Gibb, 2020).

Year	Total Population	Waste Tonnages per Year
2013	535341	213526
2014	548316	218710
2015	561669	224043
2016	575414	229530
2017	589563	235175
2018	601354	239879

The growth rate was determined using equation 1 below that represents the estimated total annual population:

$$P_n = P_o \times (1 + r)^n \quad \text{Equation 1}$$

Where:

P_n = Estimated Final Population per year

P_o = Initial Population

r = Growth Rate (%)

n = number of years

Using the 2% identified population growth rate based on the annual total population increase as per the Table 1, estimated projections for the total population per annum were calculated for the next 50 years.

A waste tonnage growth rate of 2%, in line with the population growth rate, was estimated from Table 1 and used for 50-year projections of the Estimated Final Waste Tonnage per annum, using Equation 2 below.

$$W_n = W_o \times (1 + r)^n \quad \text{Equation 2}$$

Where:

W_n = Estimated Final Waste Tonnage per year

W_o = Initial Waste Tonnage

r = Growth Rate (%)

n = number of years

From the third generation IWMP developed by the GRDM in 2020, the total organic fraction in the MSW stream sent to landfill equated to 35.6% of the total domestic waste profile (Figure 1). This percentage was used to simulate the projections of organic waste tonnage over the next 50-year period. It is to note that this percentage of organic waste was kept constant in the simulations conducted despite the population growth, based on the assumption that no interventions will be put in place by the municipality to divert this specific waste stream during the next 50 years. A conservative approach was also used assuming that the percentage of organic waste (a range between 30% and 40%) will remain constant in line with national trends (DFFE, 2018).

The Total Organic Waste Fraction per year were calculated using Equation 3 below:

$$\frac{\text{Total waste generated (tons per year)} \times 35.6\%}{\text{Total organic waste fraction (tons per year)}} = \text{Equation 3}$$

Using the waste fractions calculated above, the carbon emissions production or reduction potentials were calculated in MTCO₂eq using emission factors from the IPCC (2006) as quoted in USEPA (2016).

Table 2. Table of emission factors (IPCC, 2006; USEPA, 2016)

Waste Fraction	Landfill disposal emission factors	Anaerobic digestion emission factors	Anaerobic composting emission factors
Biogenic Food Waste	1.54	-0.04	-0.15
Garden Refuse: Green	-0.16	-	-0.12
Garden Refuse: Wood	-0.26	-	-0.12

The equation below was used to determine the methane emissions or emission reduction potential in MTCO₂eq:

$$\text{Waste quantity in tons} \times \text{emission factor} = \text{MTCO}_2\text{eq} \quad \text{Equation 1}$$

The emissions produced/reduced were calculated for a 50-year period for each of the defined scenarios selected, using the appropriate emission factors. Taking into consideration that the total volume of organic waste may not be viable for scenario 4 due to contaminants in the organic waste stream or factors such as the presence of substances not suitable for AD, assumptions were made for determining viability of organic waste for use in AD. Simulations were conducted at 5% intervals up to 40% assuming that due to contamination only a portion of the organic food waste component is viable for use in an AD facility. The results for which are discussed in the section below.

4.5 Results and Discussion

Figure 4 below depicts the historical projection of food waste and garden refuse from 2013 to 2020 along with a projection of food and garden refuse volume increases at a rate of 2% per annum over the next 50 years. It is evident from the graph below that the food waste volume increases from 22211.7 tons per year in 2020 by almost 3-fold in the projected time frame to 59784.7 tons by the year 2050. This stresses the need for the urgent implementation of alternative waste management strategies for the management of organic waste fractions to comply with the landfill bans imposed.

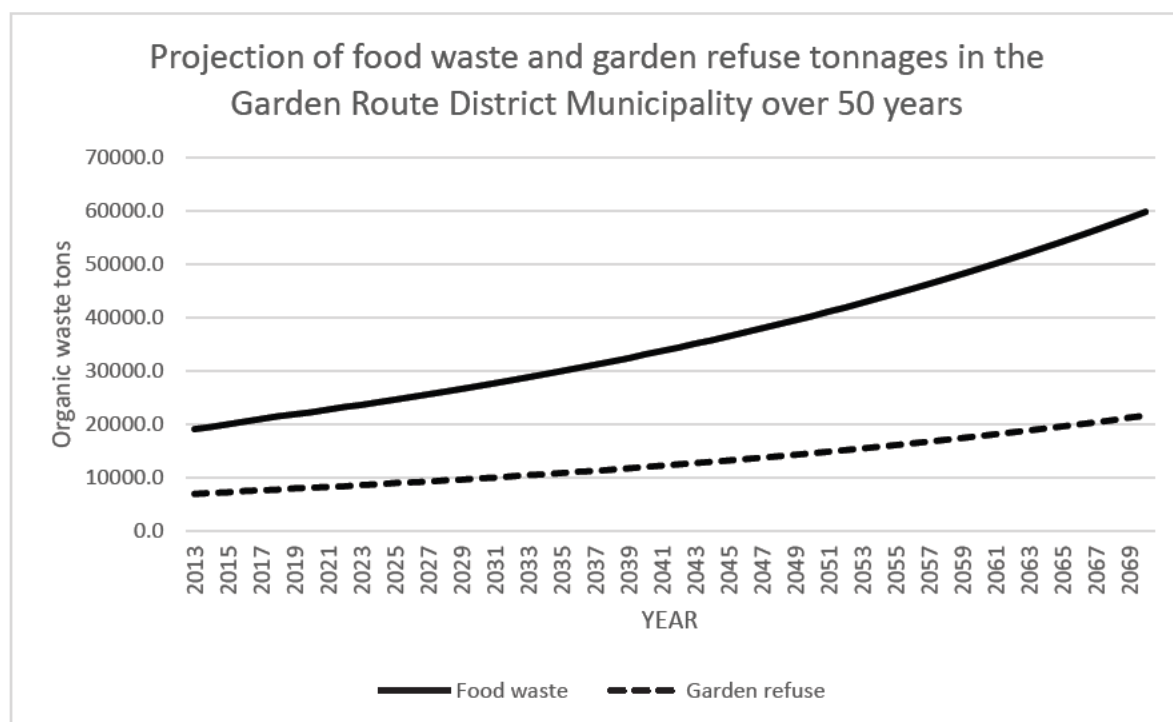


Figure 4. Projection of food waste and garden refuse tonnages in the Garden Route District Municipality from 2013 to 2070.

The estimated tonnage of food waste combined with the IPCC emission factors were used to determine a baseline scenario of the volume of methane emissions for scenario 1: The disposal of unsorted, untreated MSW to landfill or BAU as seen in Figure 4. This refers to the total volume of methane emitted through the disposal of unsorted, untreated MSW to landfill in the GRDM over the next 50 years. Figure 4 below highlights “*the risk of inaction*” by continuing with scenario 1. The net zero emissions seen in Figure 5, for the disposal of garden refuse to landfill, is the result of a significantly lower emission factor of 0.16 (IPCC, 2006) as well as

lower amounts with respect to the higher quantities of organic food waste and their associated higher emission factor of 1.54 (IPCC, 2006).

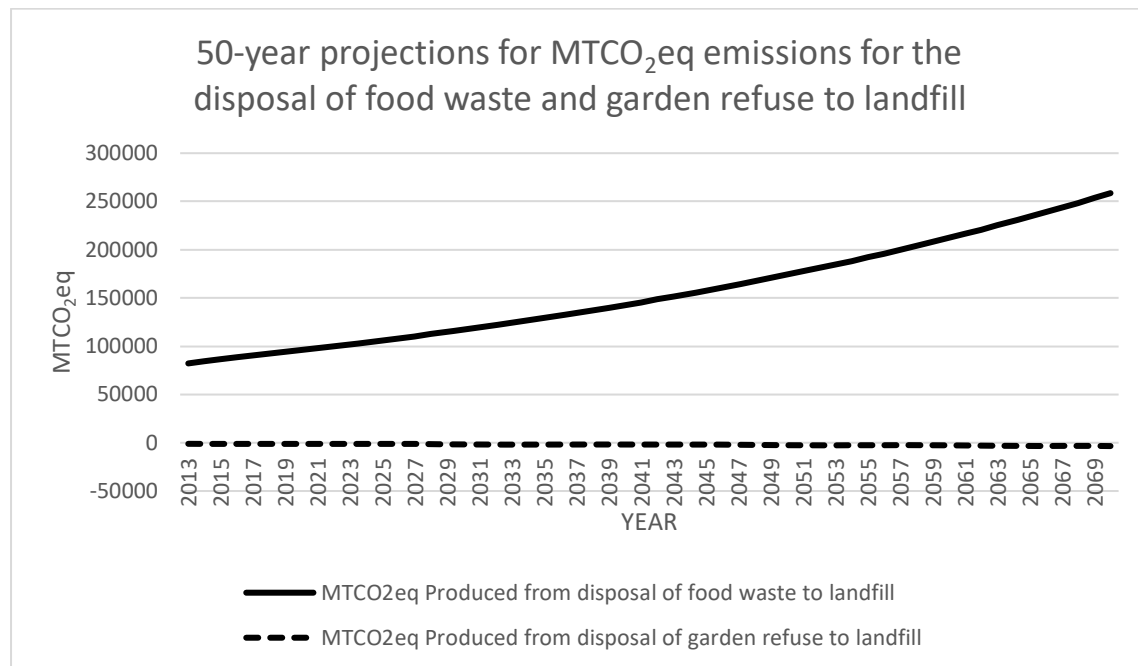


Figure 5. 50-year projections of MTCO₂eq emissions for the disposal of food waste and garden refuse to landfill (BAU).

Scenarios 1, 4 and 5 of the WROSE model were selected as they are most applicable to the management of the organic fraction municipal solid waste (OFMSW). The variances in results will determine which of the scenarios/interventions will be most relevant for the stabilisation of GHG emissions for the next 50 years. Subsequently to the development of the GHG emissions stabilisation wedge, the potential viability of the organic food waste fraction for anaerobic digestion was assessed as per discussion in the section above.

Based on Figures 4 and 5, as waste generation rates increase by more than triple in the next 50 years so do the GHG emissions from the organic waste fractions. Figures 5 and 6 below depicts the outcome of the comparison of the selected scenario:

For Scenario 1, the model depicts the steady increase of GHG emissions for both organic waste and garden refuse. This rate of GHG emissions is unsustainable for long term climate contributions due to the global warming potential of CH₄ being 25 times more harmful than that of CO₂ according to the USEPA (2021).

For Scenario 4, the introduction of AD facilities for the treatment of all organic food waste at 100% viability for digestion is shown to reduce the GHG emission levels to a stable state i.e. no upward trajectory over the next 50 years.

Should no interventions be put in place over the next 50 years, the impact of waste disposal to landfill grows exponentially. This is a direct result of the global warming potential of methane emissions from the decomposition of organic waste in landfill facilities. Figure 6 below depicts the potential for the reduction of methane emissions from 258619.33 MTCO₂eq by the 2070 through the disposal of food waste to landfill to -2391.39 MTCO₂eq through the channeling of food waste to an AD facility.

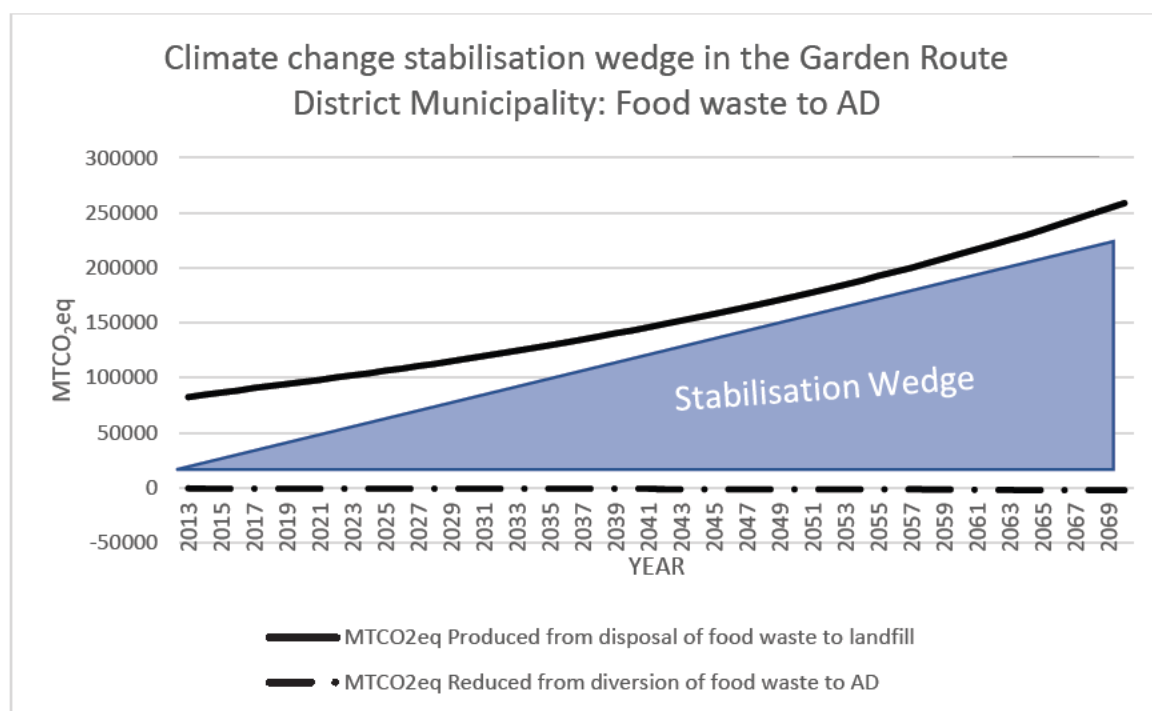


Figure 6. Climate change stabilisation wedge for 50-year projections: Comparison between food waste to landfill (BAU) versus food waste to Anaerobic Digestion (AD).

For Scenario 5, two simulations were conducted, the first being the potential GHG emission reduction composting as a treatment method for biogenic food waste fractions is shown to reduce GHG emissions to a stable level for the next 50 years, similar to that of AD as seen Figure 7 below.

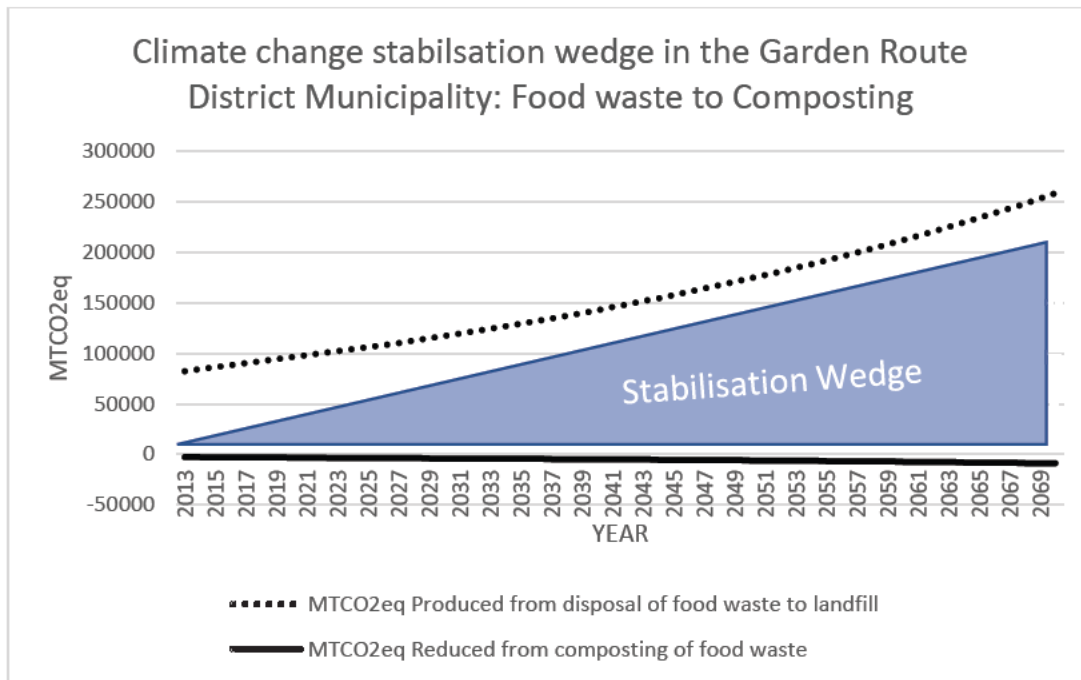


Figure 7. Climate change stabilisation wedge for 50-year projections: Comparison between food waste to landfill (BAU) versus food waste to composting.

The second simulation for Scenario 5, composting as a treatment method for garden refuse fractions is shown to reduce GHG emissions to a stable level for the next 50 years, lower than that of AD as evidenced in Figure 8.

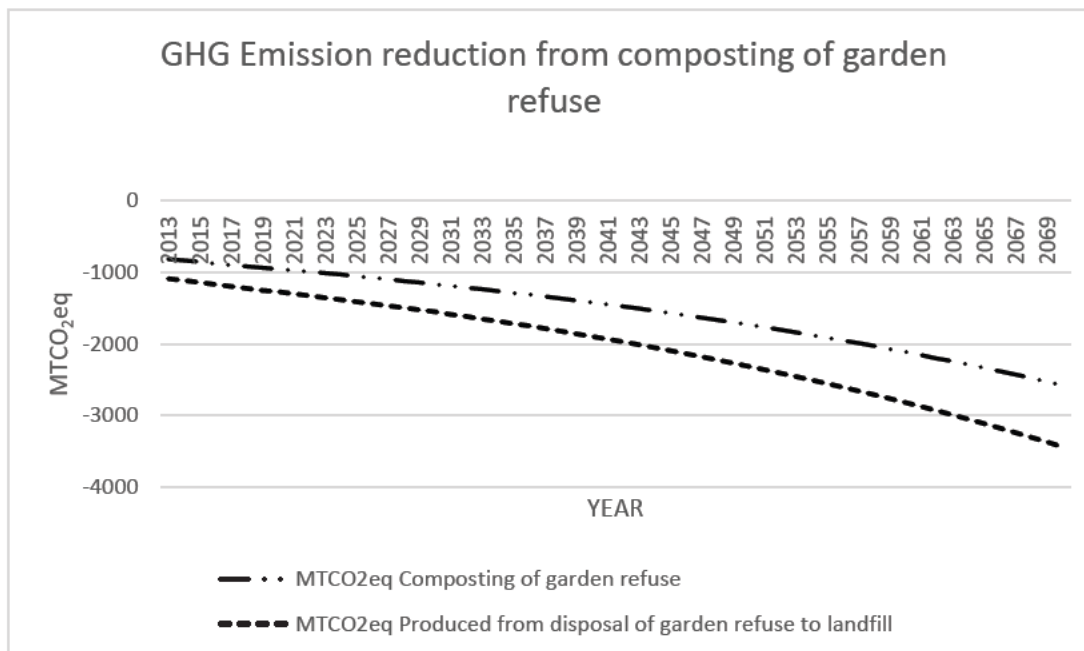


Figure 8. Comparison between 50-year projections of GHG emissions for food waste to landfill (BAU) versus food waste to composting.

The implementation of an AD facility in the Garden Route at maximum capacity reduces the GHG emissions to a stable level i.e. no upward trajectory, however, of the total waste volume generated, organic food waste accounts for 25%. Of the 25% of the total organic food waste generated, consideration is given to the potentiality that not all of the organic food waste within the 25% generated is viable for use in an AD facility. Therefore, Figure 9 below assesses the potential viability of organic waste from the total organic food waste fraction generated (25% of the total waste volume) at 10%; 20%; 30% and 40% viability. As evidenced from Figure 9 below, the larger the volume of viable organic waste for an AD facility the greater GHG emission reductions that can be achieved.

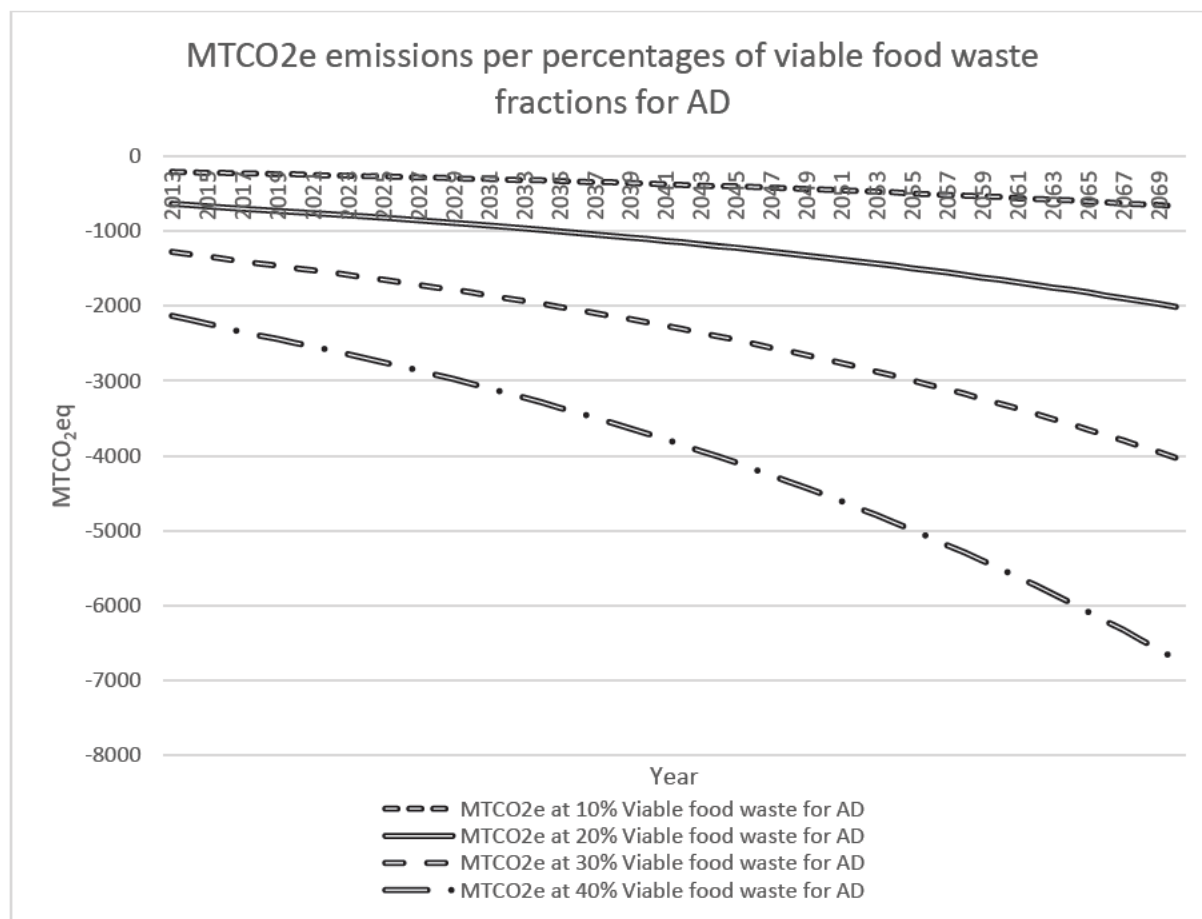


Figure 9. Projected carbon emissions reductions for various percentages of viable food waste fractions for AD.

4.6 Conclusions and recommendations for future research

This study aligns with the efforts of DFFE through the use of the multicriteria WROSE methodology to strengthen and enhance the mitigation potential analysis within the waste sector. Thus, activating optimized waste to resource management which allows for practical implementation of waste diversion from landfill. This is achieved by integrating the WROSE methodology into the mitigation strategy by technology and scenario assessments in terms of mitigation potential. The assessment of GHG emissions through the scenario BAU over a 50-year period for the Garden Route District Municipality has depicted a CO₂eq yield from 96000 MTCO₂eq in 2020 to almost triple in 50 years of >250000 MTCO₂eq by the year 2070. The assessment of mitigation strategies qualifies as a stabilisation wedge by lowering the trajectory of emissions to a stable emission volume over the next 50 years. The scenarios which are most applicable for achieving these stabilisation rates for organic waste fractions are scenario 4 and 5 of the WROSE model. This will aid the Garden Route District Municipality in achieving part of the mandate for the diversion of all organics from entering landfills by the Western Cape Government and activating aspects of the circular economy. The development of the climate change stabilisation wedge is one of the very first for a South African Municipality in the waste sector. Such a study can contribute towards future IWMP developments and municipal waste management planning within the Garden Route District Municipality.

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Chapter 5

AN ASSESSMENT OF SUSTAINED GHG EMISSION REDUCTION AND THE IMPLICATIONS OF POLICY IMPLEMENTATION FOR THE DIVERSION OF ORGANIC WASTE IN THE CITY OF CAPE TOWN

This chapter, similarly to chapter 4, assesses the GHG emissions and emission reductions that can be achieved in a metropolitan municipality level. The outcome of the study feeds directly into the development of a framework for a greenhouse gas mitigation strategy. This will contribute to national GHG emission reduction targets and overall climate change stabilization in the waste sector.

5.1 Abstract

The disposal of unsorted, untreated municipal solid waste to landfill is the most utilised method for waste management employed across South Africa. However, the need for improved waste management systems to contribute to curbing the impact of the waste sector on climate change is fast gaining momentum both at a national and global levels. This study presents an analysis of the potential for greenhouse gas (GHG) emission reductions from the organic waste fraction of municipal solid waste (MSW) in the City of Cape Town. This is established using the Waste to Resource Optimisation and Scenario Evaluation model (WROSE) in conjunction with the Intergovernmental Panel for Climate Change's (IPCC) carbon emission factors. The WROSE model was used in the selection of appropriate integrated waste management scenarios for the study. A comparison was conducted between the emissions from the current scenario 1, landfill disposal and/or (Business as usual – BAU) with other more optimised scenarios which, for this study is anaerobic digestion and composting as waste treatment methods for the organic waste fraction. This study incorporates 3 main analyses. The first being the assessment of GHG emissions from the disposal of the food waste and garden refuse fraction to landfill. This is then compared to the emission reduction potential that can be achieved through the diversion of the total food waste fraction to anaerobic digestion (AD) and the total garden refuse fraction to composting as climate mitigation pathways. The second is the assessment of the GHG emission reduction potential from the implementation of the policy aimed at the diversion of 50% of the organic waste fraction from landfill by 2022 and the diversion of 100% of the

organic waste fraction by 2027 (DEA&DP, 2022). The third and final outcome of the study is the assessment of the potential GHG emissions reduction achievable based on the viability of the food waste fractions that can be recovered for anaerobic digestion. The food waste and garden refuse fractions, were extracted from the most recently available waste stream analysis conducted in the CoCT which was 8.1% and 15.2% respectively of the total waste fraction. This increases in line with the projected population increase assuming no interventions are put in place. The outcome of the BAU scenario shows an increase of GHG emissions by up to three times the current emissions rate with no interventions in place. The GHG emission reduction from the introduction of AD and composting as a mechanism for the treatment of organic food waste and garden refuse stabilizes the emissions to current rates over the next 50 years. Should the policy for the diversion of organic waste from landfill be implemented with full effect, significant reductions in GHG emissions are achievable. However, municipalities do not currently possess the necessary infrastructure and financial resources to manage the large amounts of waste that will be diverted from landfill. Therefore, there is a need to develop a framework to capacitate municipalities with the necessary mechanisms to handle such large diversions of organic waste.

5.2 Introduction

The implementation and improvement of sustainable waste management practices goes beyond sanitation as the waste sector plays an important role in its contributions to greenhouse gases (GHG) as well as global warming. However, the connection between waste and climate change is not fully understood, this causes a potential hindering effect on the achievement of the Nationally Determined Contributions (NDCs) and sustainability. In many developing countries, the standard practice for the management of municipal solid waste is the collection and disposal to landfills or open dumps. This can be attributed to the lack of available resources to implement integrated waste management practices. The South African waste sector is estimated to contribute to 4.1% of the total greenhouse gas emissions in the country (DFFE, 2022). It is further estimated that 76% of the total municipal solid waste fraction in the country is disposed of into landfill (DFFE, 2022). In efforts to curb the contribution of various sectors such as waste on global warming, national government has developed tools such as the mitigation potential analysis (MPA) to assess mitigation options and potential reductions that can be achieved in three scenarios:

The MPA model projects national GHG emissions in various sectors in three scenarios

- A 'Without Measures' (WOM) projection of emissions from 2000 to 2050 assuming that no climate change mitigation actions have taken place since 2000.
- A 'With Existing Measures' (WEM) projection, which incorporates the impacts of climate change mitigation policies and measures implemented to 2019.
- A 'With Additional Measures' (WAM) projection, which assumes that existing, pipeline and potential future climate change mitigation policies and measures are implemented (DFFE, 2022).

The purpose of this study is to test the hypothesis that South African municipalities have the potential to contribute significantly to the reduction of GHG emissions from the waste sector by incorporating climate considerations into the waste management decision making discourse. Thereby contributing towards meeting national targets aimed at GHG emission reduction. This is due to the fact municipalities are the main custodians of municipal solid waste in South Africa. The City of Cape Town (CoCT) is located in the Western Cape Province and is one of eight metropolitan municipalities in South Africa. The Western Cape Provincial Government has issued a ban of zero organic waste to landfill by 2027, with a 50% diversion of organic waste from landfill target by 2022 (DEA&DP, 2022). This study aims to assess the potential contribution from the organic waste fraction to global warming in the CoCT over a 50-year period. This study, using the WROSE model assesses the GHG emissions from the food waste fraction and the garden refuse fraction to landfill (BAU), followed by the assessment of the inclusion of anaerobic digestion and composting as a waste treatment mechanism for the organic waste fractions. Furthermore this study analyses the impact of the successful implementation of waste diversion policies on GHG emission reduction for the CoCT.

5.3 Case Study Area

The City of Cape Town (CoCT) metropolitan municipality was selected as the case study municipality for this study as it is the largest municipality in the Western Cape region. The CoCT is located in southern peninsula of the Western Cape province and is one of eight metropolitan municipalities in the country with a surface area of approximately 2445km² (IWMP, 2021). The CoCT is the capital as well as the economic hub of the Western Cape Province.

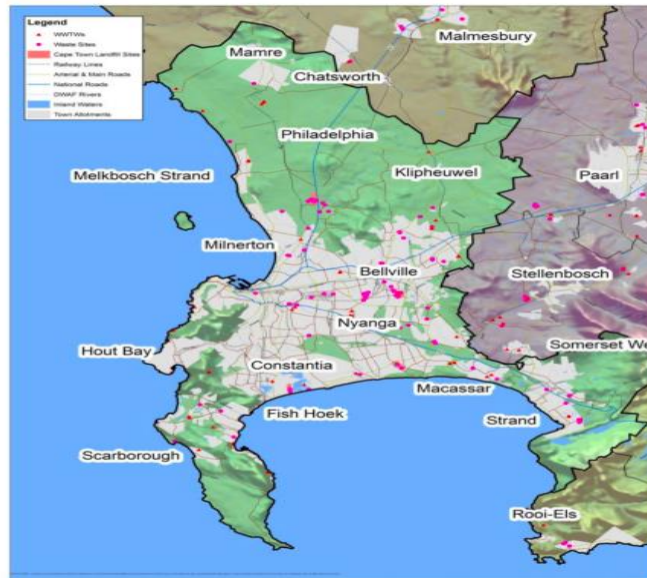


Figure 1. Map of the City of Cape Town Metropolitan Municipality (IWMP, 2021)

The estimated population of the CoCT according to the 2021 integrated development plan (IDP) was at 4 678 900 people which is approximately 66% of the population of the Western Cape Province. The population density of the CoCT is 1913 persons per km². The CoCT has an estimate of 1 462 156 households of which 80.6% is formal dwellings (IDP 2021).

Figure 2 below outlines the waste profile of the CoCT, The data on waste composition was extracted from the City of Cape Town's 3rd Generation Integrated Waste Management Plan (IWMP) 2022-2027, which is determined by the characterization research conducted in 2011 on the residential waste stream.

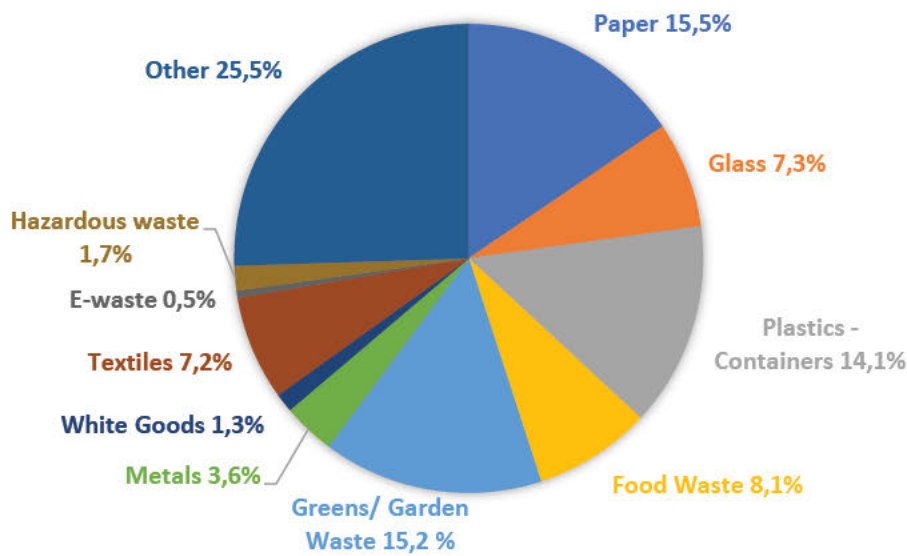


Figure 2. Waste profile of the household waste fraction in the CoCT (IWMP, 2021)

As seen in figure 2, the food waste fraction comprises 8.1% of the total waste stream, while green and garden waste comprises 15.2%. Due to a lack of more recent waste stream data, the values outlined in the waste profile will be used for this study.

Similar to other municipalities in the Western Cape, waste diversion targets for the city of Cape Town:

- 50% diversion of organic waste from landfill by 2022 (short term/immediate target)
- 100% diversion of organic waste from landfill by 2027 (5-year target)

The diversion of the organic fractions of municipal solid waste has the potential to reduce greenhouse gas emissions from the municipal solid waste sector and contribute to the greater emission reduction targets of nationally determined contributions. Furthermore the City of Cape Town has already implemented landfill gas extraction technology in three landfill facilities which contributes to emissions reductions.

Figure 3a. below represents the historical constructed MSW generation data which indicates that the MSW per capita in the year 2000 was 451 kg/cap/yr or 1.24 kg/cap/day. Figure 3b. depicts the growth rate between MSW per capita and GDP capita, it can be observed that there is a modest increase of GDP per capita until 2016 while MSW per capita remains practically constant until 2013.

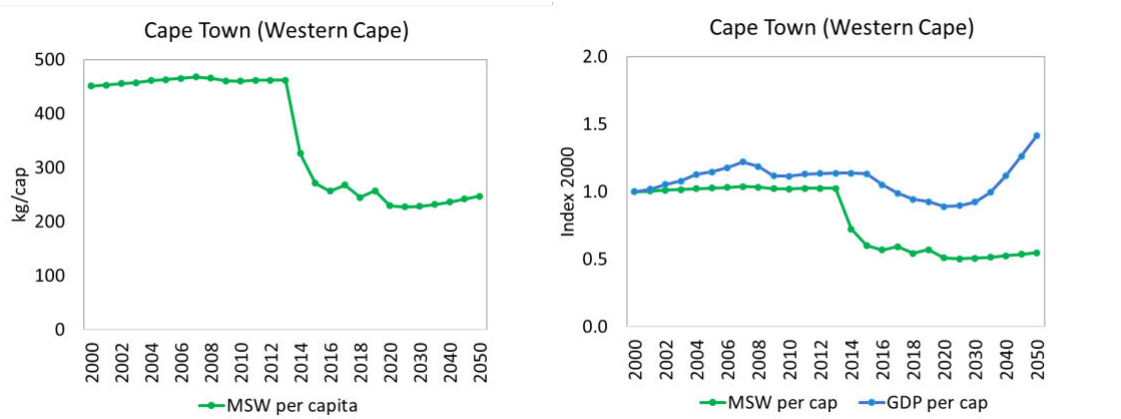


Figure 3. a. MSW per capita and b. MSW per capita and GDP per capita in the City of Cape Town (IIASA 2022)

Based on waste data reported, there is a decline of MSW generation per capita in 2013 and 2019. Estimates suggest that in the year 2020 residents in the Cape Town generated 229 kg/cap/yr (0.63 kg/cap/day) which is around 50% lower than the estimate in 2000. By 2050, it is expected that MSW per capita will increase by 8% compared to 2020 figures. Between 2013 and 2019 MSW per capita decreases 44% while GDP shows a decrease between 2017 until 2035. Towards 2050 GDP per capita is expected to grow much faster than the MSW per capita.

5.4 Methodology

In order to conduct this study, boundary conditions were set to achieve specific outcomes. Within the City of Cape Town, only two comprehensive waste characterisation studies have been conducted. The first in 2007 and the second in 2011 (IWMP, 2022). For the purpose of this study, the outcome of the 2011 waste characterisation study served as a baseline for future data projections and forecasting. The availability of recent updated figures was a key gap in conducting the GHG emissions estimations. Therefore, embedding forecasting capabilities into the WROSE model will allow for a better understanding of waste quantities for emissions estimates.

Waste fractions were extracted from the CoCT 3rd generation IWMP, which contained the most recent waste stream analysis conducted in 2011, within which the total food waste fraction was 8.1% of the total MSW fraction and the garden refuse fraction was at 15.2%. This was kept consistent over the 50-year forecasting period as a conservative approach.

The first set of analysis conducted for the CoCT was based on the assumption that no policy or alternative technology interventions were put in place to reduce the amount of waste sent to landfill or to reduce the GHG emissions from MSW. Furthermore, the analysis considered the treatment of 100% of the food waste and garden refuse fraction to establish a best case scenario for the development of a framework for a greenhouse gas mitigation strategy as well as to align with the provincial policy.

The second set of assumptions considered the interventions of the Western Cape Government which assumes the GHG emissions reductions that could occur should the targets be met according to the 4th Generation IWMP for the City of Cape Town.

The Western Cape Provincial Government has in the IWMP stipulated organic waste diversion targets for the city of Cape Town

- 50% diversion of organic waste from landfill by 2022 (short term/immediate target)
- 100% diversion of organic waste from landfill by 2027 (5year target)

The WROSE Model

For the purpose of this study the Waste Resource Optimization and Scenario Evaluation Model (WROSE) was used to identify suitable mitigation pathways for the diversion of the food waste and garden refuse fractions. The WROSE model was developed as a decision support methodology that can be employed by municipal officials and decision makers to determine which integrated waste management mechanism can be used to meet the highest needs of the municipality. The model includes 5 key scenarios, the disposal of MSW to landfill, landfilling with gas extraction, recycling, AD and composting. Detailed scenarios are presented in figure 4 below. In accordance with the Africa waste management outlook, across the African continent, the collection and disposal of unsorted MSW into landfills or open dumps is the mostly widely practiced method for waste management across Africa. Therefore, the first scenario selected for this study is scenario 1 or business as usual. Anaerobic digestion has the potential to serve not only as an alternative waste treatment solution but can contribute to the supply of energy. The use of AD in Asian and European countries both with centralised and decentralised solutions has been widely tested. Therefore the second scenario selected for this study is scenario 4. For the purpose of this study, the following four scenarios were considered for long term climate mitigation planning:

Scenario 1: The disposal of unsorted untreated MSW to landfill (Worst case scenario)

Scenario 2A: The disposal of unsorted untreated MSW to landfill with landfill gas generation and flaring (BAU)

Scenario 2B: The disposal of unsorted untreated MSW to landfill with landfill gas extraction and electricity generation

Scenario 4: Treatment of the organic food waste fraction through anaerobic digestion

Scenario 5: The treatment of food waste and garden refuse to composting. were selected as the most appropriate for the management of the food waste and garden refuse fractions (Trois & Jagath 2011).

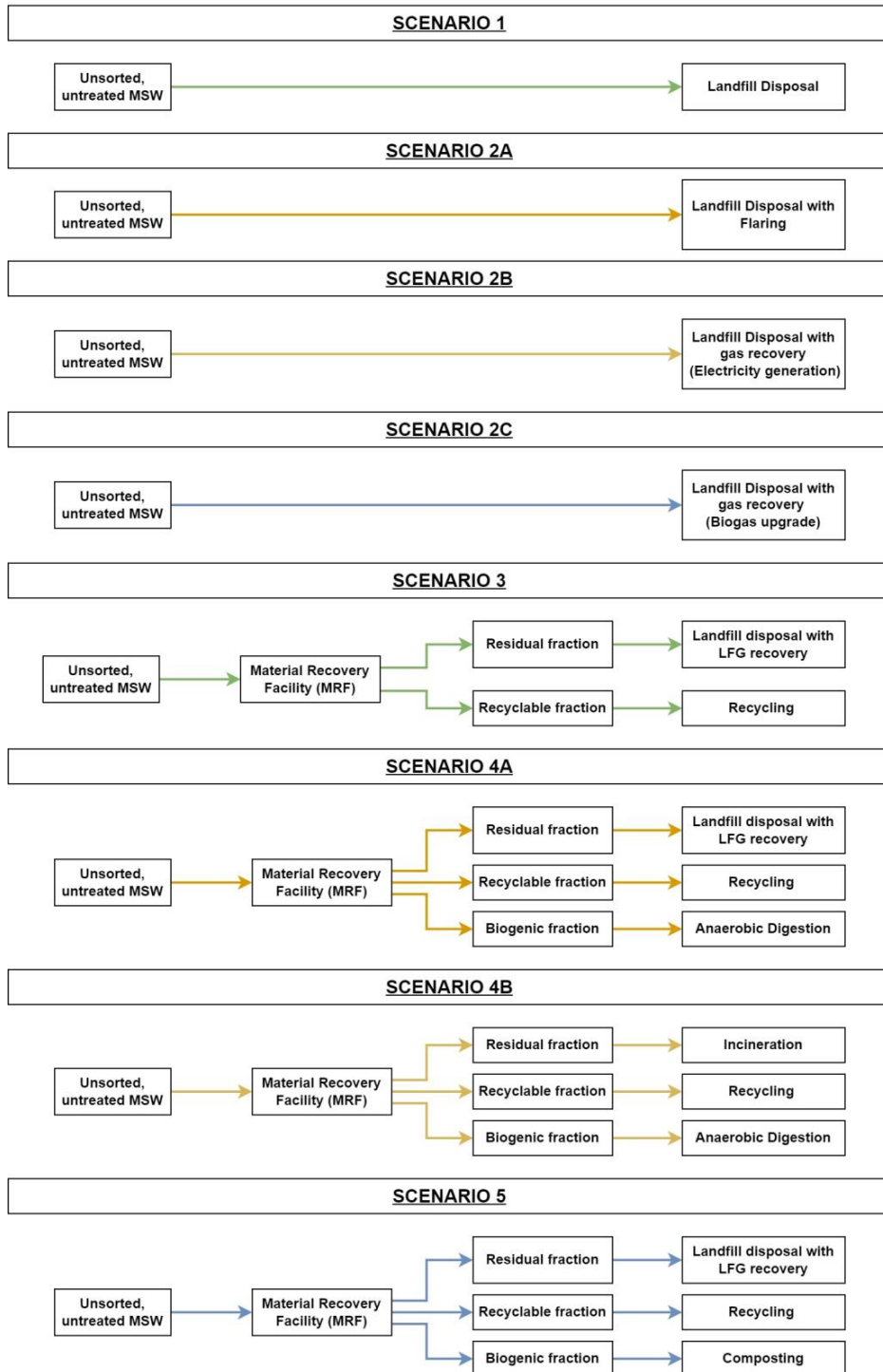


Figure 4: WROSE scenarios schematic (Dell'Orto and Trois, 2022, Trois and Jagath, 2011, Trois et al,2023)

In order to determine the population growth for this study equation 1 below was used to estimate the total annual population:

$$P_n = P_o \times (1 + r)^n \quad \text{Equation 1}$$

Where:

P_n = Estimated Final Population per year

P_o = Initial Population

r = Growth Rate (%)

n = number of years

(Kissoon & Trois, 2023)

Using the population growth established using the equation above, the increase in waste tonnages were forecast in line with population increase. This was at a rate of 2% per annum. Where data is available, the final waste tonnage was established using the equation below.

$$W_n = W_o \times (1 + r)^n \quad \text{Equation 2}$$

Where:

W_n = Estimated Final Waste Tonnage per year

W_o = Initial Waste Tonnage

r = Growth Rate (%)

n = number of years

(Kissoon & Trois, 2023)

The Total Organic Waste Fraction per year were calculated using Equation 3 below:

$$\frac{\text{Total waste generated (tons per year)} \times \text{percent of organic waste}}{\text{Total organic waste fraction (tons per year)}} = \quad \text{Equation 3}$$

(Kissoon & Trois, 2023)

By using the established waste tonnages above to project GHG emissions and emission reduction potential in MTCO_{2eq} the algorithm below was added to the WROSE model in order to enable the model to conduct long term emissions projections:

$$AccGHG_y = \sum_{i=n}^y \sum_t (WA_y \times WF_i \times RR_t \times EF_t)$$

Equation 4

Where:

- **GHG_y** represents the greenhouse gas emission for year y.
- **AccGHG_y** represents the accumulated Greenhouse gas emission from initial year n to year y.
- **n** represents the initial year
- **t** represents the different waste management technologies.
- **WA_y** represents the amount of waste for the year y.
- **WF_i** represents the percentage of waste fraction for i waste type.
- **i** represents the waste type (e.g., organic, plastics, paper, etc.).
- **RR_t** represents the recovery rate for technology t.
- **EF_t** represents the GHG emission factor for technology t.

Based on the waste tonnages established using the equation above, carbon emissions production or reduction potentials were calculated in MTCO₂eq using the IPCC (2006) emission factors as quoted in USEPA (2016). The table below is a summary of the emission factors utilised for this study.

Table 1. IPCC emission factors (IPCC 2006; USEPA, 2016)

Waste Fraction	Landfill disposal Emission factor	LFG recovery	Recycling	Anaerobic Digestion Emission Factor	Anaerobic Composting Emission Factor
Food waste	1.54	0.36		-0.04	-0.15
Garden Refuse: Green	0.16	-0.26			-0.12
Garden Refuse: Wood	0.26	-0.69			-0.12

In to order establish the GHG emissions and emission reduction potential in $MTCO_2eq$ the equation below was used:

$$Waste\ quantity\ in\ tons \times emission\ factor = MTCO_2eq \quad \text{Equation 2}$$

A study conducted on recycling in developing countries as a mechanism for sustainable waste management determined that within 19 of the case studies conducted, a recovery rate of recyclables with a minimum of 5% to a maximum of 40% was identified (Troschinetz and Mihelcic, 2009). The recovery rate of the organic fraction extracted ranged from 17% to a maximum of 80%. In addition, numerous studies have reported a wide range of diversion rates for organic and garden refuse wastes. In a study conducted by Wang et al. (2020), it was found that between 54.4 to 91.9% of garden refuse could be treated through composting. According to a second study, 5% to 18 % of organic waste can be managed via anaerobic digestion and composting (Clarke, 2018, Maria et al., 2020). Therefore, for the purpose of this study, the recovery rate for the organic waste fraction is assumed with a minimum of 5% to a maximum of 40% based on literature, a rate achieved by many developing countries and similar to South Africa. The GHG emissions calculated from the equations above using the selected recovery rates were projected for the next 50 years, the outcome of which is discussed below.

5.5 Results and discussion

Figure 5 below depicts the forecasted increase in population and waste tonnages from 2020 to 2070 in the CoCT at a growth of 2% per annum..

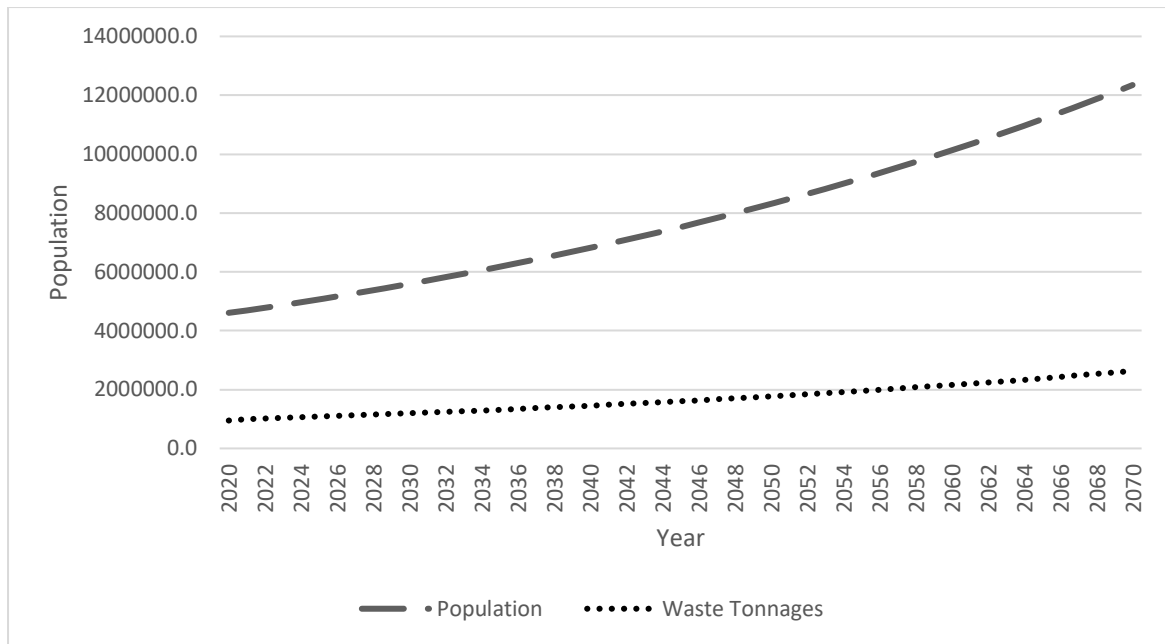


Figure 5. Projection of population and waste tons over a 50-year period in the City of Cape Town

Figure 5 shows an increase in the population of the CoCT to rise from 4607601 in 2020 to 12346737.5 in 2070. The total amount of waste is projected to increase from 947909 tons in 2020 to 2632315 tons in 2070

Figure 6 below depicts the increase in waste tonnages for food waste and garden refuse from 2020 to 2070 without the consideration of any policy measures or interventions to divert either of these streams over the next 50 years.

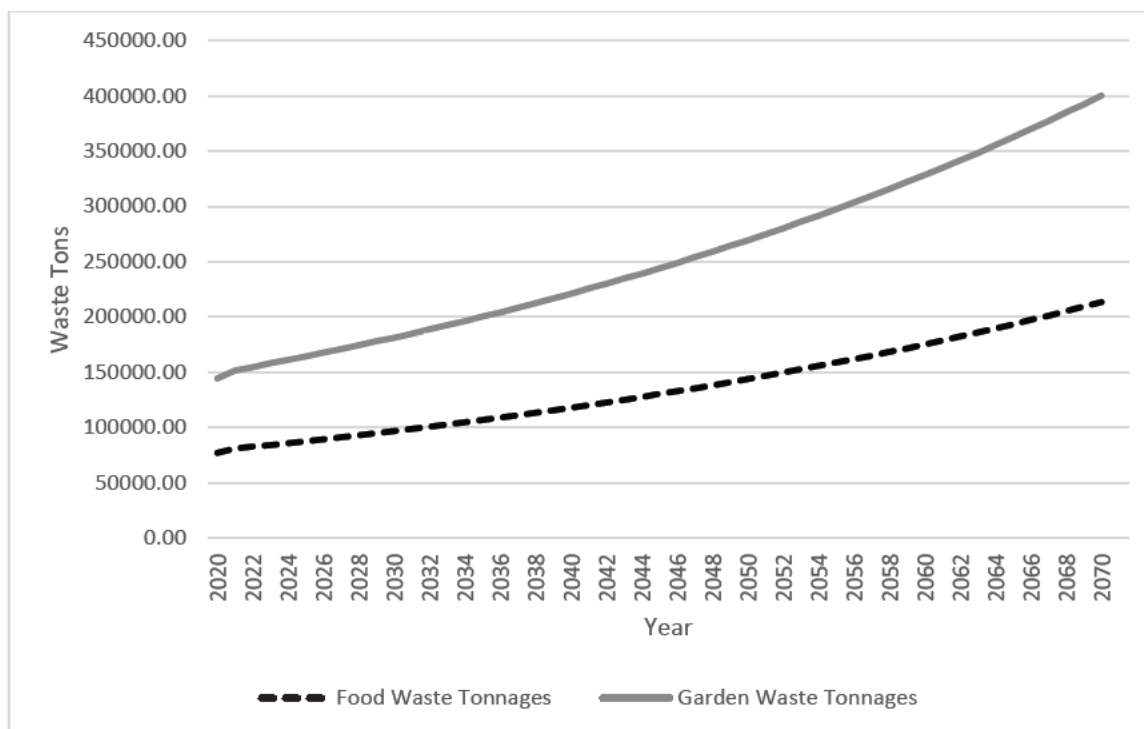


Figure 6. Projection of waste tons for food waste and garden refuse over 50 years in the City of Cape Town

The food waste fraction is the lowest at 8.1% of the total waste stream and is projected to increase from 76780.63 tons in 2020 to 213217.52 tons in 2070. The garden refuse fraction is the second highest at 15.2% of the total waste stream. The garden refuse fraction is projected to increase from 144082.2 tons in 2020 to 400111.9 tons on 2070. The tonnages identified above are imperative to the next steps of the study as this forms the basis of the input data needed for determining the GHG emissions from the food waste and garden refuse waste streams.

Figure 7 below is the projected resulting emissions from the disposal of the biogenic food waste fraction and garden refuse fraction to landfill.

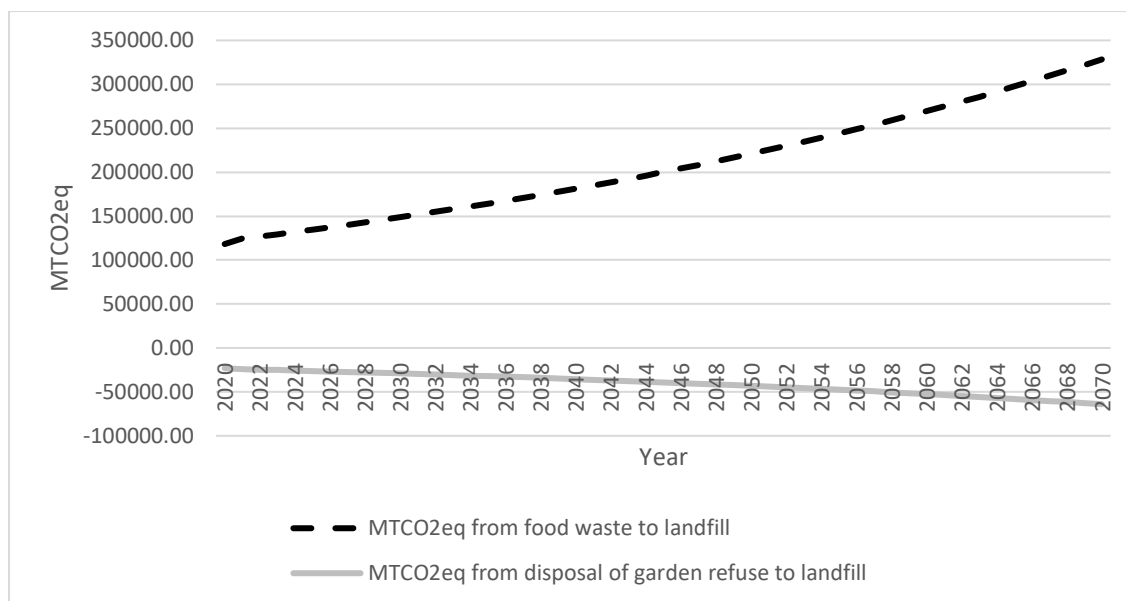


Figure 7. 50 Year projection of MTCO₂eq emissions for the disposal of food waste and garden refuse to landfill for the CoCT.

The emissions seen in Figure 7 for the disposal of the garden refuse fraction of the total waste stream to landfill, is due to a considerably lower emission factor of -0.16 (IPCC, 2006) despite the quantity of garden refuse being higher than that of the food waste fraction of 15.2% in the CoCT. Despite the lower quantities of organic food of 8.1% of the total waste fraction, the associated higher emissions are due to an emission factor of 1.54 (IPCC, 2006). However the projected emissions from the disposal of food waste to landfill appears to increase by more than double from 118242.17 MTCO₂eq in 2020 to 328354 MTCO₂eq by 2070. These projections reflect the need to consider long term emissions from waste and what the implications of these emissions are for climate considerations.

Figures 8, 9, 10 and 11 below depicts the emissions reduction achievable through the introduction of alternative treatment technologies for the organic waste and garden refuse fraction of MSW. Figure 8 first projects the emission reduction potential from the disposal of the food waste fraction to landfill with landfill gas recovery with two applications, the first is landfill gas recovery with flaring and the second is landfill gas recovery with electricity generation.

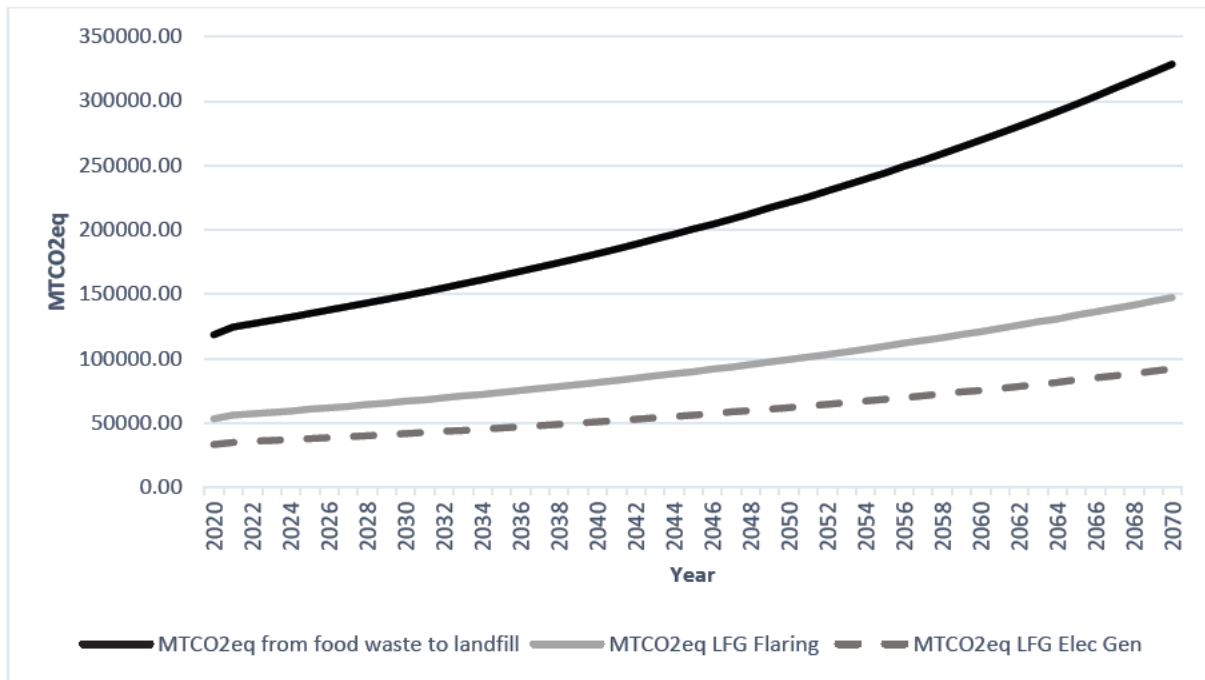


Figure 8. Methane emissions and emissions reduction potential from food waste to landfill with landfill gas extraction in MTCO₂eq

At present, the CoCT has implemented landfill gas recovery projects in three landfills. Therefore, this scenario represents the business as usual scenario and the greenhouse gas emissions reduction achievable when compared with the emissions from specifically disposing of the waste to landfill with no landfill gas recovery.

Figure 9 below illustrates the greenhouse gas emissions and emission reduction potential that is achievable from scenario 4 the disposal of food waste to landfill and food waste to AD.

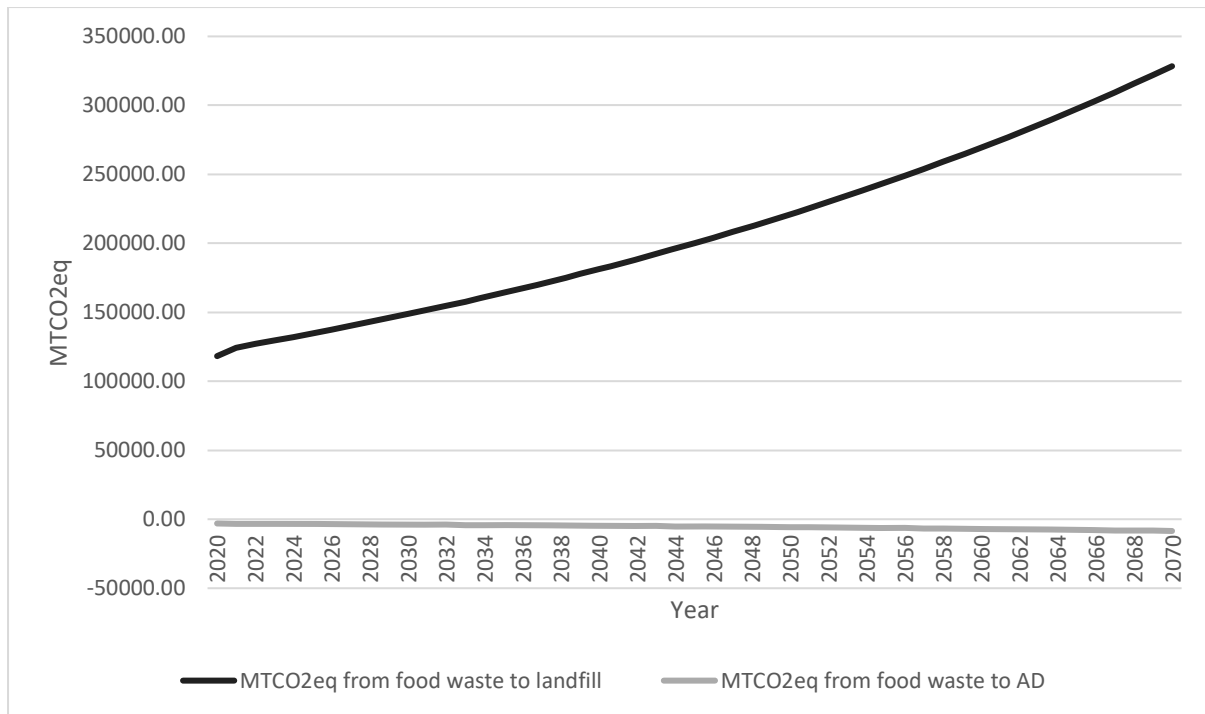


Figure 9. Methane emissions in MTCO₂eq produced from food waste to landfill and reduced from food waste to AD CoCT

The GHG emissions from the disposal of food waste to landfill is projected to increase from 118242.17MTCO₂eq in 2020 to 220973.49 MTCO₂eq in 2070. Whereas the estimated GHG emission reduction that can be achieved through the treatment of the food waste fraction from landfill is expected to decrease from -3071.2252MTCO₂eq in 2020 to -5739.571 MTCO₂eq in 2050.

Figure 10 below are the outcomes of scenario 5, the composting of the total food waste fraction. Similar to that of AD, the composting of the food waste fraction reduces the GHG to a stable level over the next 50 years.

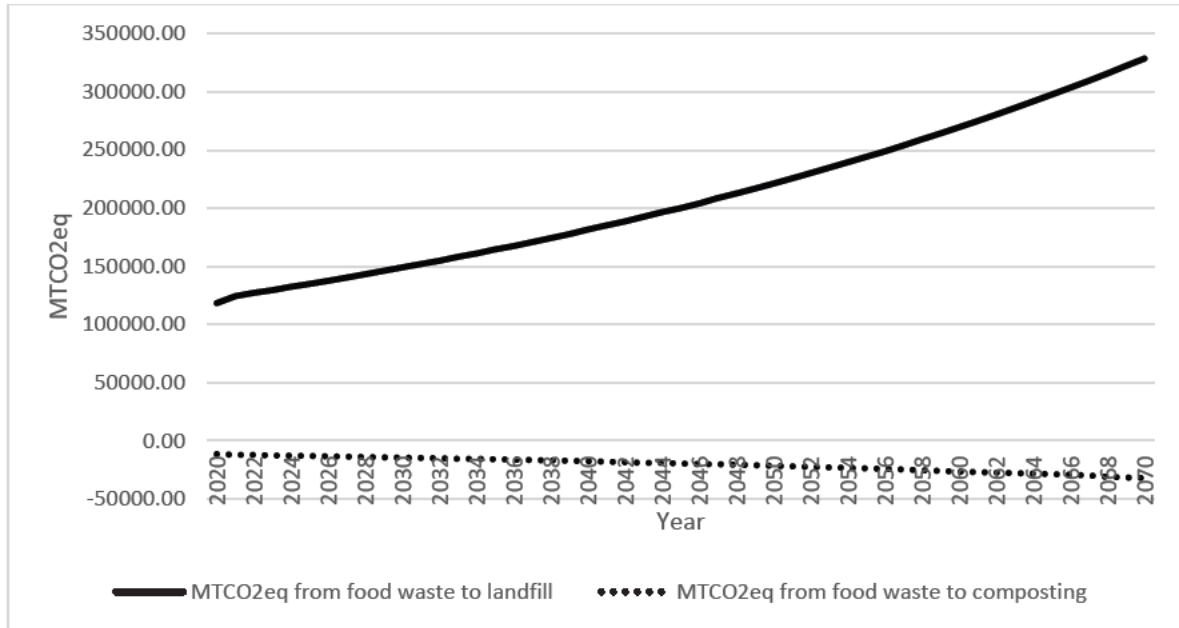


Figure 10. Climate change stabilisation over a 50-Year period for the CoCT from food waste to composting

Figure 11 depicts the emission reductions achievable from the diversion of the garden refuse fraction out of landfill into composting. Through this the GHG emissions could potentially to be reduced to a stable level for the next 50 years. The higher level of emission reduction achieved through the disposal of garden refuse to landfill is due to the lower emission factors as outlined in Table 1.

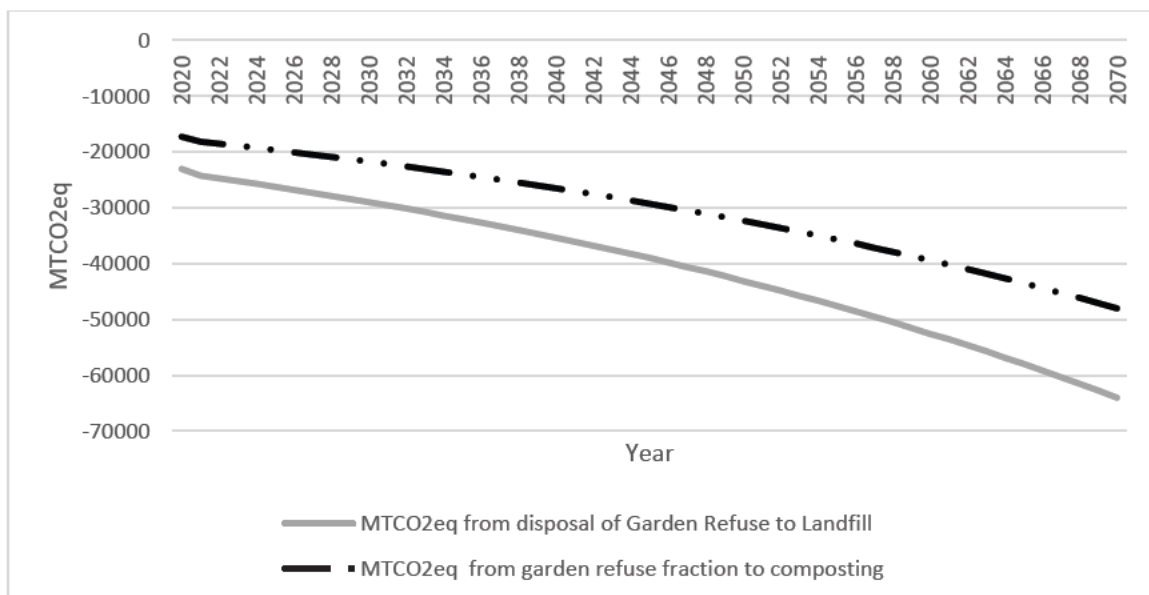


Figure 11. 50-year projection of GHG emission reduction from composting of garden refuse for the CoCT

Figure 12 below is the projected outcome of the implementation of policy 50% organic waste diversion in 2022 and 100% by 2027. This is represented for both the food waste fraction as well as the cumulative GHG emissions that can be achieved through the composting of garden refuse combined with the anaerobic digestion of food waste is seen below.

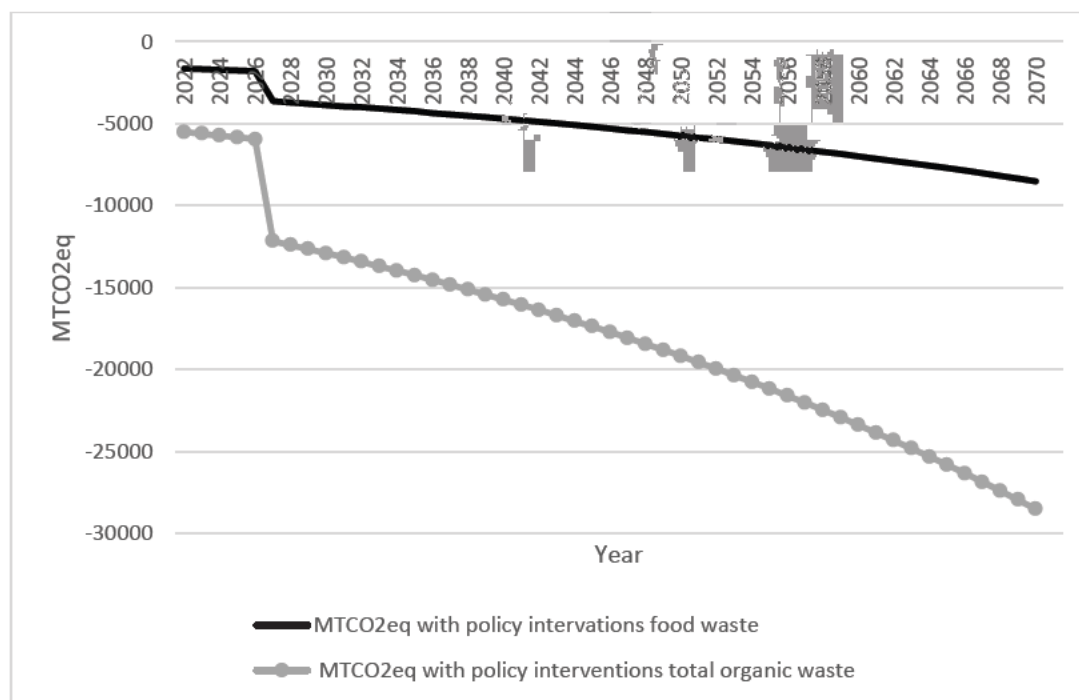


Figure 12. Methane emissions in MTCO2eq achievable from the implementation of policy targets.

With the policy implementation of a 50% diversion rate for the food waste fraction, GHG emissions depict a steady decrease from -1648.3318MTCO2eq in 2022 to -1784.2073 MTCO2eq in 2026. This is followed by the implementation of the second phase of the policy implementation for the diversion of 100% of the food waste fraction. Due to the 100% diversion rate, a sharp further decrease in the emissions can be seen from 2027 from -3639.783MTCO2eq up to -8528.7007MTCO2eq in 2070. The emission reduction achievable through the implementation of the policy to divert the organic fraction of municipal solid waste from landfill is reliant on the separation of the organic waste fraction, either through separate at source or through mechanical pre-treatment.

The cumulative GHG emission reductions are also illustrated in the figure below taking into consideration the GHG emission reduction that can be achieved from the total organic waste

fraction. Similar to the food waste fraction, there is a steady reduction in emissions from 2022 to 2026 assuming a 50% diversion of organic waste, with a sharp decline in emissions from 2027 when 100% of the organic fraction is diverted from landfills.

Figure 13 below depicts the outcome of the GHG emission reduction potential at various food waste recovery rates over the next 50-year period for the extraction of viable food waste fractions for AD. This analysis was conducted at 5%, 15%, 25%, 35% and 40% recovery rates.

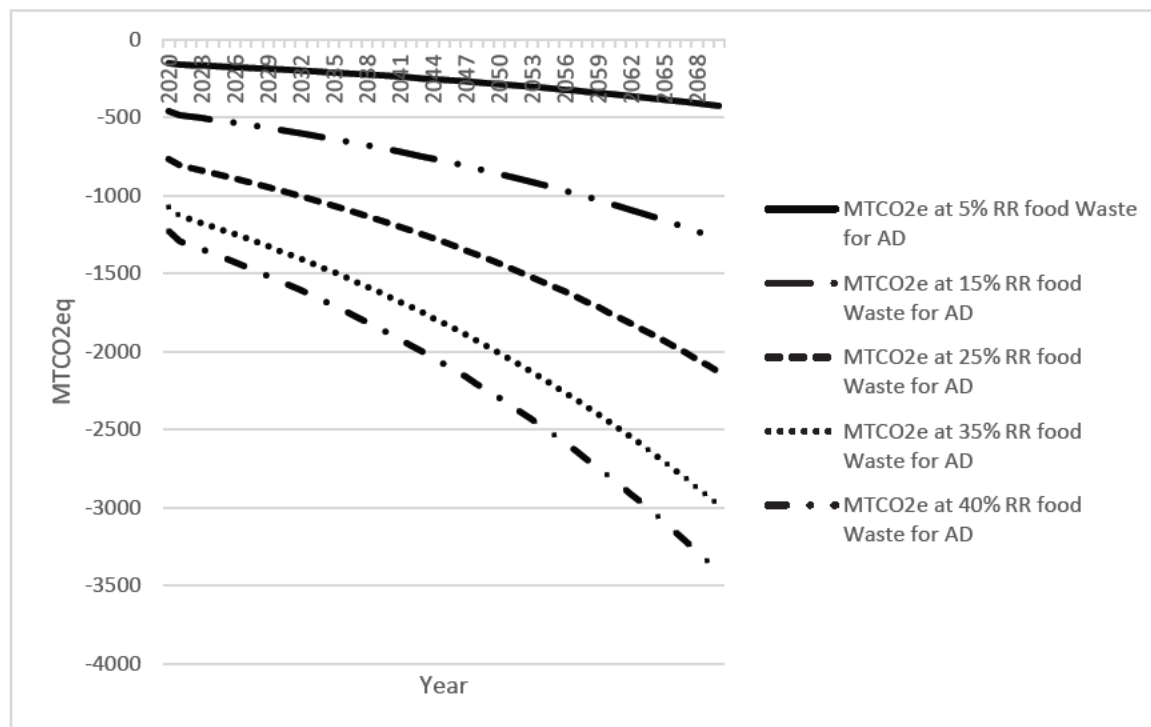


Figure 13. Methane emissions in MTCO₂eq reduced from food waste to AD in the CoCT over a 50-year period at various recovery rates

The figure depicts that the higher the recovery rate of viable food waste fractions, the higher the emission reduction potential that can be achieved. By the year 2070 at a recovery rate of 5% the emissions achievable are -426.43504MTCO₂eq whereas at a 40 % recovery rate the emission reductions increase to -3411.4803 MTCO₂eq. However, South African Municipalities lack the required human resources and financial capital to achieve high organic waste recovery rates. This is compounded with the lack of available alternative waste treatment infrastructure to manage the waste fractions extracted in the interim.

5.6 Conclusion

The aim of the study was to determine the most appropriate GHG mitigation pathways for the management of the organic waste fraction diverted from landfill in the City of Cape Town. The key outcome of the study is that potential emissions can be reduced within the CoCT through the implementation of scenarios 4 and 5 (composting and AD) which have the potential to reduce GHG emissions to a stable state. Furthermore, the study assessed the potential GHG emissions can be reduced through the implementation of policy initiatives aimed at the diversion of organic waste from landfill of 50% by 2022 and 100% diversion by 2027. Through this, significant emissions reductions can be achieved in a shorter time frame. However, due to the lack of available infrastructure, capacity and resources at municipal level, achieving this level of stabilization requires strategic planning and interventions. Therefore there is a need to develop an institutional framework for a greenhouse gas mitigation strategy that will assist municipalities in achieving sustained carbon emission reductions. This bottom up approach has the potential to meet the needs of national targets through the implementation of local initiatives. Some of the limitations of the study include the absence of a standardized reporting method for MSW data and the lack of available, updated and reliable data sources.

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Chapter 6

PRELIMINARY STEPS FOR THE DEVELOPMENT OF A FRAMEWORK FOR AN ADAPTABLE GREENHOUSE GAS MITIGATION STRATEGY FOR SOUTH AFRICAN MUNICIPALITIES: A CASE STUDY OF THE CITY OF CAPE TOWN AND THE GARDEN ROUTE DISTRICT MUNICIPALITY

This chapter forms the crux of the study as it incorporates the findings of chapter 4 and 5 for the development of the framework for a greenhouse gas mitigation strategy that will ultimately contribute to climate change stabilization in the waste sector. The framework suggests a phased approach with immediate-term, short-term, medium-term and long-term interventions to achieve sustained carbon emission reductions.

6.1 Abstract

Municipal solid waste in South Africa is primarily disposed of into landfill facilities. Therefore, there is a need to mitigate the impacts of the disposal of solid waste to landfill. One key impact of the disposal of solid waste to landfill is its contribution to GHG emissions and climate change. South Africa like other developing countries, contains within its boundary both urban and rural communities. South Africa comprises of eight metropolitans, 44 districts and 205 local municipalities. The amount of waste generated and disposed of differs from one municipality to the next therefore the GHG emissions produced differs from one municipality to the next. However, as population congregates in metropolitan and district municipalities, these are therefore the higher emitters of GHG's due to the higher amounts of waste generated and disposed of into landfills. This study conducted a comparative analysis of the methane emissions and emission reductions that could be achieved through the implementation of specific integrated waste management strategies in a metropolitan and a district municipality. The WROSE model was employed for the selection of the appropriate integrated waste management strategies for the study from the disposal of mixed municipal solid waste to landfill (Business as usual – BAU) with a more optimised scenario such as anaerobic digestion. The study areas chosen are the City of Cape Town and the Garden Route District Municipality. The research presents the potential methane emissions and emission reductions that could be achieved in each of the case study municipalities over the next 50 years using the

Intergovernmental Panel for Climate Change's (IPCC) carbon emission factors. The outcome of the study determined that for optimum greenhouse gas mitigation to be achieved, an integrated approach to the recovery of the organic food waste fraction needs to be considered. The study proposes a strategy which embodies short-, medium- and long-term targets that can be tailored to suit municipal needs.

6.2 Introduction

Across the globe, the impacts of climate change are more frequently visible.

Developing countries can be considered among the most susceptible to these impacts. Therefore, climate mitigation considerations should be embedded into all strategic and development planning. The municipal solid waste sector contributes a significant fraction to greenhouse gas emissions in South Africa, further to this, municipalities are faced with the issue of rapid urbanization which contributes to a rise in waste generation. Municipalities in South Africa also face the issue of depleting landfill airspace, this combined with the need to reduce GHG emissions places municipalities in position to consider waste treatment options that not only serves as resource recovery but also to include climate change mitigation in the decision making process. The South African environmental legislative landscape has developed significantly over the years to deal with the pressures of rapid urbanization on the environment. The National Environmental Management Act of 1998, being the first to come into effect. The National Environmental Management: Waste Act of 2008 was introduced to manage the increased waste generated through increased urbanisation and industrialisation. Despite the introduction of such legislative mechanisms, South Africa's governmental structure follows a five year electoral cycle, the consequence of which hinders the long term development of integrated waste management mechanisms (Godfrey et al, 2019). However, in 2019 the South African Department of Forestry, Fisheries and Environment, (DFFE) placed a ban on all forms of liquid waste to landfill. Through the introduction of such a ban, the Western Cape Government has implemented policies for the ban of organic waste to landfill due to the liquid content of the organic waste fraction (Anders and Coetzee 2022). Therefore, municipalities in the Western Cape are required to find alternative waste management solutions for the organic waste fraction. The Western Cape Province is located on the West Coast of South Africa is home to one metropolitan municipality, five districts and 24 local municipalities. The Western Cape Government conducted a metanalysis study of the waste characterization studies conducted in the province to determine what problem waste streams are in the province that could allow for planning at regional level. In accordance with the study conducted the outcome determined

that the organic waste fraction in the province accounted for an average of 35.2% of the total waste stream (Anders and Coetzee 2022).

At national level the South African government has developed the mitigation potential analysis (MPA) tool which builds a strategy for climate mitigation at national level using average data. This does not necessarily translate to an applicable strategy at a municipal level. The primary objective of this study is to examine the potential methane emissions from the organic waste fraction in the City of Cape Town and the Garden Route District Municipality. Thereafter to propose pathways to reduce GHG emissions through the consideration of a portfolio of technology options which could reduce emissions. The purpose of this assessment is to understand the contribution the municipal solid waste sector could make in greenhouse gas emissions and to guide the development of a framework which mainstreams climate mitigation considerations at the core of waste management decision making. A comparative analysis of the methane emissions that could potentially be reduced through the implementation of optimised waste management scenarios for organic food waste in a district municipality versus a metropolitan municipality over a 50-year period. The outcome of which will be used to create a framework using a bottom up approach for a greenhouse gas mitigation strategy starting at a municipal level.

6.3 Study Area

The Western Cape Province is the third largest contributor to South Africa's gross domestic product (GDP) with an approximate contribution of 14% of the country's total GDP (Wesgro, 2023). The City of Cape Town (CoCT) is the only metropolitan municipality within the Western Cape Province and is responsible for 9.9% of the South Africa's total GDP (Wesgro, 2023). The CoCT is one of eight metropolitan municipalities in the country with a surface area of approximately 2445km² (City of Cape Town, 2022). The CoCT is the capital as well as the economic hub of the Western Cape Province. Therefore, the CoCT contributes significantly to the amount of waste generated in the province and consequently the resultant emissions. The CoCT, however has already begun implementing landfill gas extraction projects in two of its existing facilities in efforts to reduce its emissions from landfill.

The second municipality selected for this study is the Garden Route District Municipality (GRDM). The GRDM is located in the southern-eastern coast of the Western Cape Province and is the third largest district municipality in the Western Cape with a surface area of

approximately 23331km² as per the 2020 Integrated Waste Management Plan (Gibb, 2020). The GRDM consists of 7 local municipalities, these are Mossel Bay, Bitou, Knysna, George Oudtshoorn, Kannaland and Hessequa. The inland areas of the GRDM are characterised strongly by rural settings with farms and small towns. The GRDM contributes approximately 8.8% to the GDP of the Western Cape Province (COGTA, 2020). The GRDM is currently in the process of developing a regional landfill facility, this is due to several local municipalities running out of available landfill airspace. This, combined with the need to divert organic waste from landfill, puts the GRDM in a position to incorporate climate change into the decision making process through the implementation of integrated waste management strategies.

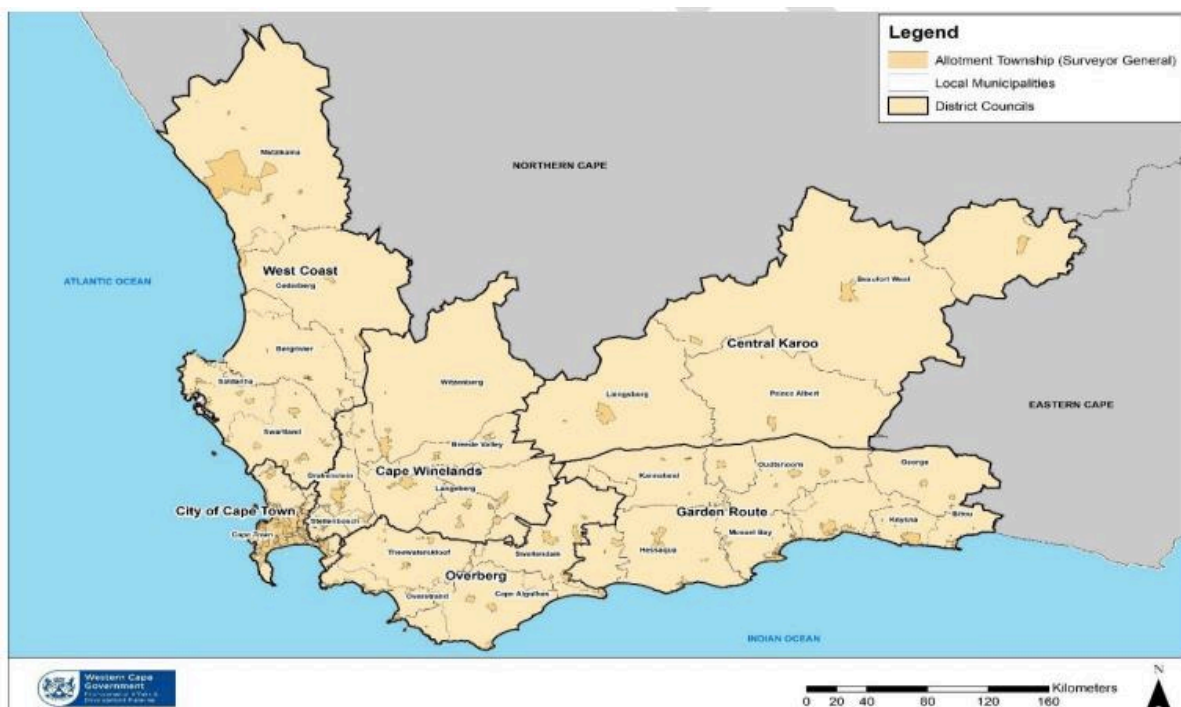


Figure 1. Map of the Western Cape Province (DEA&DP 2022)

Figure 2 below outlines the waste profile of the CoCT and the GRDM municipalities.

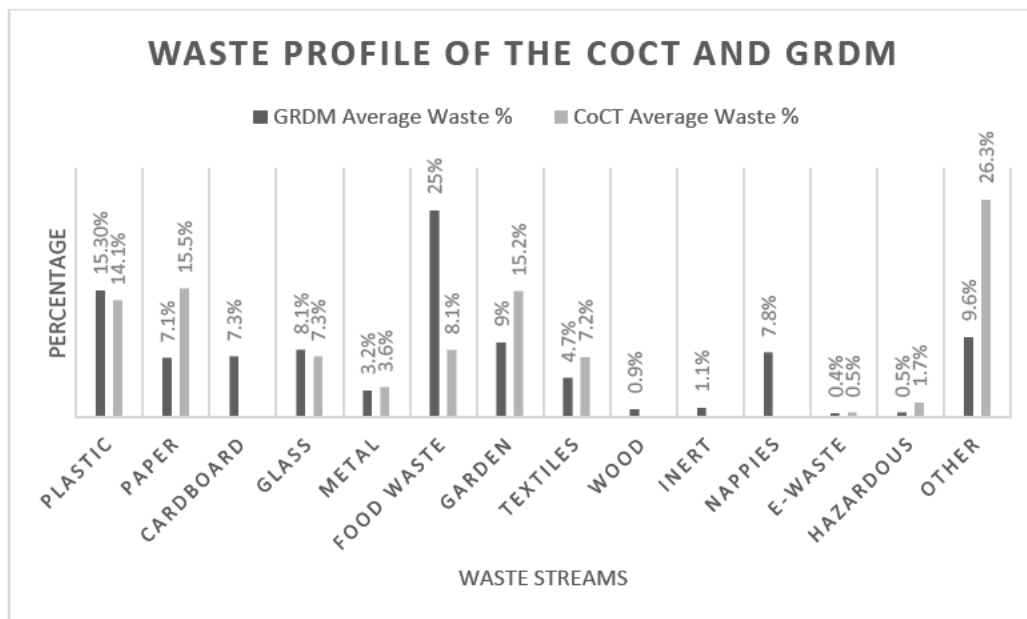


Figure 2. Waste profile of the City of Cape Town and the Garden Route District Municipality

The waste data in the figure above was developed using data extracted from the most recent integrated waste management plans of the CoCT and the GRDM based on the waste characterisation studies conducted at each of the municipalities. Figure 2 depicts the difference in the waste profile of a district municipality as opposed to a local municipality. The waste profile is of highest importance for the development of a climate change strategy in each municipality as this influences the applicable technology portfolio for each municipality. The technology portfolio for the development of the greenhouse gas mitigation strategy is dependant on the quantities of waste available.

6.4 Methodology

This study proposes to forecast long term emissions from each of the selected case study municipalities through the use of the advanced WROSE model. Thereafter, the study utilizes the information forecast in conjunction with a multi criteria decision analysis technique for the development of a framework for a climate mitigation strategy.

The first step in the development of a climate mitigation study was the analysis of integrated waste management plans (IWMP's) which informed the first stage of data collection for the analysis of methane emissions and emission reduction in the GRDM and the CoCT. Through

this data collection process waste generation quantities and qualities were extracted from pre-existing IWMPs per municipality.

In order to standardise the analysis for the study to ensure that the municipalities are comparable, specific boundary conditions were assigned, these boundary conditions are:

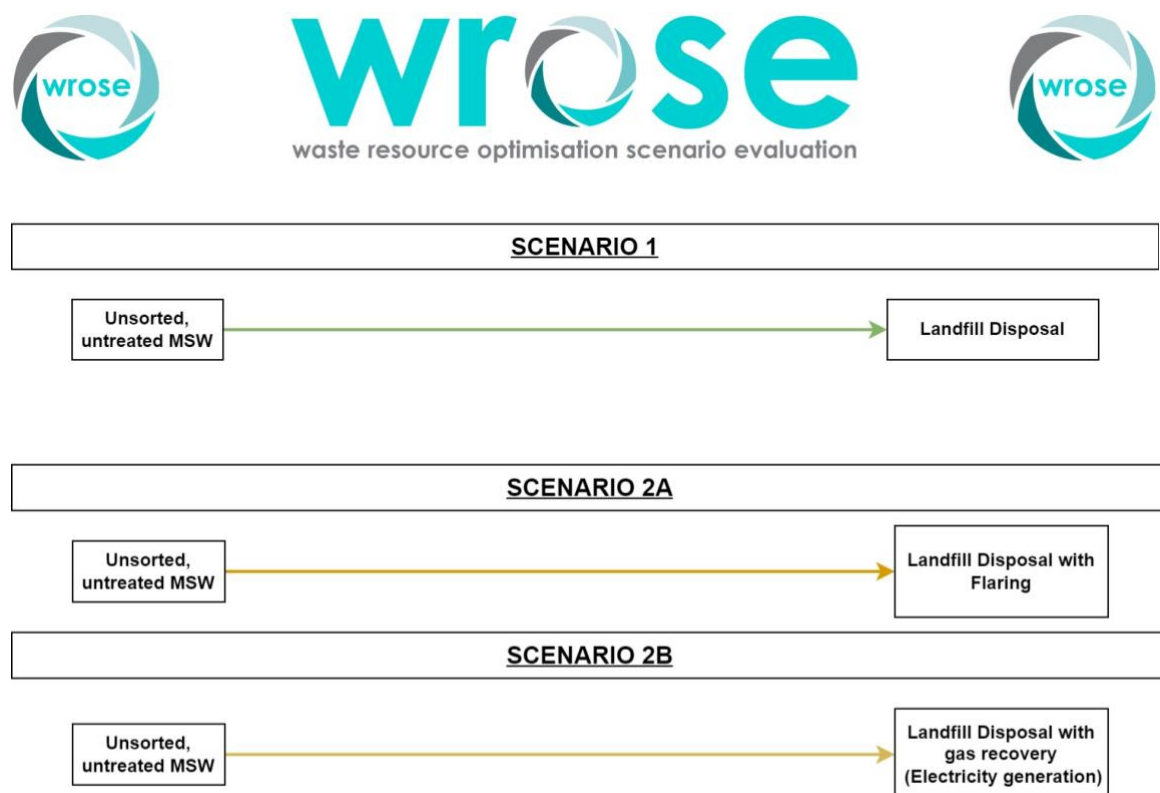
- The waste stream selected for the analysis of methane emission and emission reduction as a focal point of this study is organic food waste.
- Data on the total amount of waste diverted and disposed into landfills is obtained from the City of Cape Town solid waste management website database. However due to the inconsistencies in the data reported, waste data projections for the next 50 years were calculated in line with the population growth at 2%.
- The total organic fraction was determined using the percentages of waste reported in the waste characterisation studies in each of the latest IWMP's. The organic waste percentages have been kept consistent throughout the analysis despite the increase in population. This is due to the lack of updated waste characterisation data.

The second step of the study was the inputting of the available waste data into the advanced Waste Resource Optimization and Scenario Evaluation (WROSE) model. The WROSE model is a decision support methodology with the purpose of establishing the potentiality for GHG emission reduction from the municipal solid waste stream. This is accomplished through the selection of a specific technology portfolio relevant to the problematic waste streams at hand. The model was incorporated into this study for the purpose of scenario identification which is most applicable to the management of the organic waste fraction. The WROSE model was developed with the aim of integrating various indicators of sustainability as core features for decision making. These indicators of sustainability include environmental indicators such as GHG emissions and emission reduction, landfill space savings and waste diversion rates. Social indicators include job creation potential, health risks and public participation. Institutional indicators include applicable policy and legislative instrument applicable to specific technology options and lastly economic indicators include high level capital and operational costs of each technology option (Trois & Jagath 2011).

The scenarios anchored as the baseline scenarios for the WROSE model, range from the collection and disposal of unsorted municipal solid waste to landfill to more complex optimised technology portfolio options. These include but are not limited to landfill gas extraction from

the disposal of unsorted waste to landfill, the extraction of the recyclable fraction via a material recovery facility to go to recycling, the extraction of the organic waste fraction via a material recovery facility for use in anaerobic digestion, the extraction of the organic fraction via a material recovery facility to be used for composting (Trois and Jagath, 2011). For the purpose of this study three scenarios were selected from the options above, scenario 1, the disposal of unsorted municipal solid waste to landfill, scenario 2, the disposal of municipal solid waste to landfill with gas extraction and 4a, the extraction of the organic waste fraction via a material recovery facility for use in anaerobic digestion. Using these selected scenario's, GHG emissions from organic waste to landfill and the GHG emissions that can be reduced through the introduction of AD as a treatment technology will be assessed. Figure 3 below presents a schematic of the scenarios used for this study.

Figure 3 below outlines the scenarios of the WROSE model selected for this study graphically.



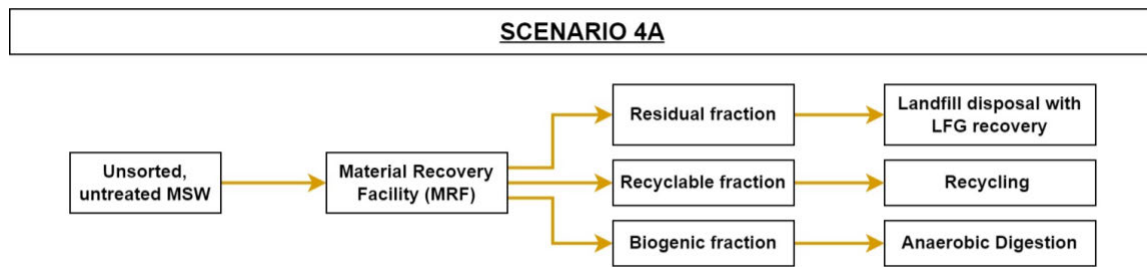


Figure 3. WROSE scenarios 1, 2A, 2B and 4A schematic (Dell'Orto and Trois, 2022, Trois and Jagath, 2011, Trois et al, 2023)

Advancements in the WROSE model were made to incorporate long term emissions projections and was developed using the methodology below. In order to estimate the potential total population for the next 50 years per annum per municipality, equation 1 below was used to forecast the estimated total annual population from 2020 to 2070:

$$P_n = P_o \times (1 + r)^n \quad \text{Equation 1}$$

Where:

P_n = Estimated Final Population per year

P_o = Initial Population

r = Growth Rate (%)

n = number of years

(Kissoon & Trois, 2023)

For the purpose of this study the population growth rate which was established using the equation above formed the basis for determining annual waste tonnages per municipality. Various studies have determined the linear relationship between population and waste generation to a 99% accuracy. Therefore the increase in waste tonnages were established in line with population increase for each of the case study municipalities. Where data is available, the final waste tonnage was established using the equation below.

$$W_n = W_o \times (1 + r)^n \quad \text{Equation 2}$$

Where:

W_n = Estimated Final Waste Tonnage per year

W_o = Initial Waste Tonnage

r = Growth Rate (%)

n = number of years

(Kissoon & Trois, 2023)

The total organic waste fraction in tons per municipality, per year was derived using Equation 3 below based on the percentage of organic waste fractions reported in the latest IWMP reported data:

$$\text{Total waste generated (tons per year)} \times \text{percent of organic waste} = \text{Total organic waste fraction (tons per year)} \quad \text{Equation 3}$$

(Kissoon & Trois, 2023)

The waste tonnages established using the equation above formed the basic input data to determine the carbon emissions production or reduction potentials per annum over the next 50 years per case study municipality. The GHG emissions and emission reductions were calculated in MTCO₂eq using the IPCC (2006) emission factors as quoted in USEPA (2016). The table below is a summary of the emission factors used for this study.

Table 1. IPCC emission factors (IPCC 2006; USEAP 2016)

Waste Fraction	Landfill disposal Emission factor	LFG recovery	Recycling	Anaerobic Digestion Emission Factor	Anaerobic Composting Emission Factor
Biogenic Food waste	1.39	0.36		-0.04	-0.12
Garden Refuse: Green	-0.21	-0.26			-0.05
Garden Refuse: Wood	0.26	-0.69			-0.05

The advanced WROSE model was applied to determine long term GHG emissions and emission reduction potential of each of the scenarios identified above. The outcome of which fed directly into the framework for a climate mitigation strategy for municipal solid waste management. In order to project the GHG emissions and emission reduction potential in MTCO₂eq the equation below was used:

$$AccGHG_y = \sum_{i=n}^y \sum_t (WA_y \times WF_i \times RR_t \times EF_t)$$

Equation 3

Where:

- **GHG_y** represents the greenhouse gas emission for year y.
- **AccGHG_y** represents the accumulated Greenhouse gas emission from initial year n to year y.
- **n** represents the initial year
- **t** represents the different waste management technologies.
- **WA_y** represents the amount of waste for the year y.
- **WF_i** represents the percentage of waste fraction for i waste type.
- **i** represents the waste type (e.g., organic, plastics, paper, etc.).
- **RR_t** represents the recovery rate for technology t.
- **EF_t** represents the GHG emission factor for technology t.

The outcome of the analysis feeds into the development of the framework for the climate mitigation strategy through guiding how integrated waste management strategies can be implemented to reduce the impacts of organic waste on climate change. A multicriteria method was used to determine what factors should be taken into consideration for the development of the framework. Using the MDCA technique, the proposed framework is discussed below.

6.5 Results and Discussion

Figure 4 below depicts the projection of the total population increase over the next 50 years at a rate of 2% per annum.

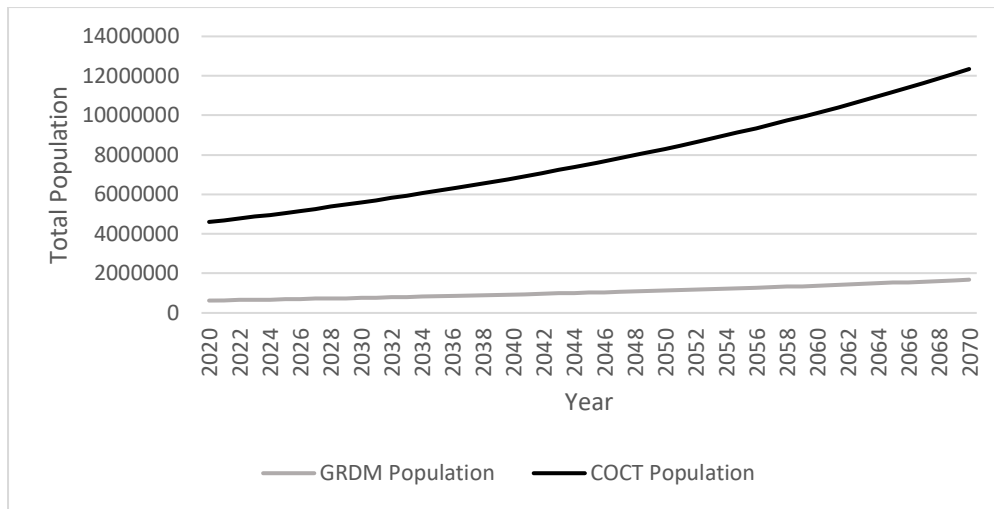


Figure 4. Population projection for the CoCT and GRDM over a 50-year period

The total population in the City of Cape Town in the year 2020 is at 4607601 which is 636% higher than that of the Garden Route District municipality for which the total population in the year 2020 was estimated at 625649. Due to the City of Cape Town being a metropolitan with a significantly larger population, the population projection increase for the year 2070 is forecasted at 12346737 whereas the population in the Garden Route District is forecasted to 1683989 by the year 2070.

The total projected population per annum was used to determine waste generation per annum in each of the selected case study municipalities, therefore, the projected amount of waste generated is projected at the same rate and the total population growth. The total waste tonnages for the next 50 -year period is depicted in figure 5 below.

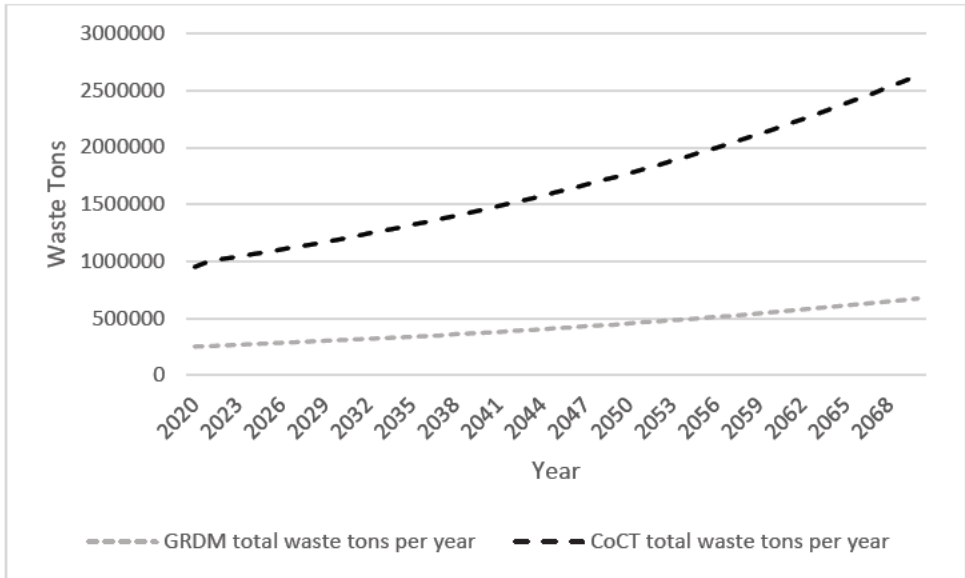


Figure 5. Total waste projection for 50 years for the CoCT and the GRDM

The total amount of waste in the City of Cape Town is expected to grow from 947909 tons in 2020 to 2632315 tons by 2050. This is an increase of 178% more than the total waste generated in 2020. Whereas the total amount of waste generated in the GRDM in 2020 is 249570 and increases by 169% to 671739 tons. It is evident from the graph below that as population levels increase, so does the amount of waste generated.

Figure 6 below depicts the organic waste projections for both the CoCT and the GRDM over the next 50 years.

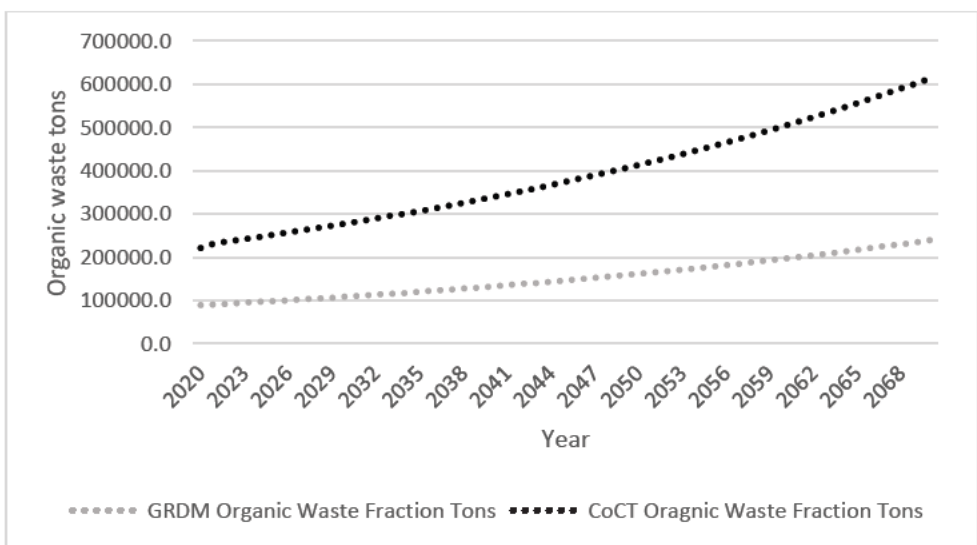


Figure 6. Total organic waste projection for the CoCT and GRDM for the next 50 years

The organic waste fraction for each municipality was determined based on the most recent waste characterization study conducted. The City of Cape Town’s most recent waste characterisation study was last conducted in the year 2011. The outcome of which determined the total combined organic fraction to be at 23.3% as per the third generation IWMP. Using this fraction of 23.3% the total organic waste fraction was projected for the next 50 years. The Garden Route District Municipality conducted a waste characterisation study across the district between 2015 and 2019. The total organic waste fraction extracted from the GRDM’S latest IWMP is at 35.6%. The organic fraction for the CoCT is seen to increase from 220862.8 tons in 2020 to 613329.4 tons in 2070. Whereas the GRDM increases from 88846.8 tons in 2020 to 239138.9 tons in 2070.

Figure 7 below depicts the GHG emissions in MTCO₂eq produced from the disposal of the total food waste fraction in both municipalities to landfill.

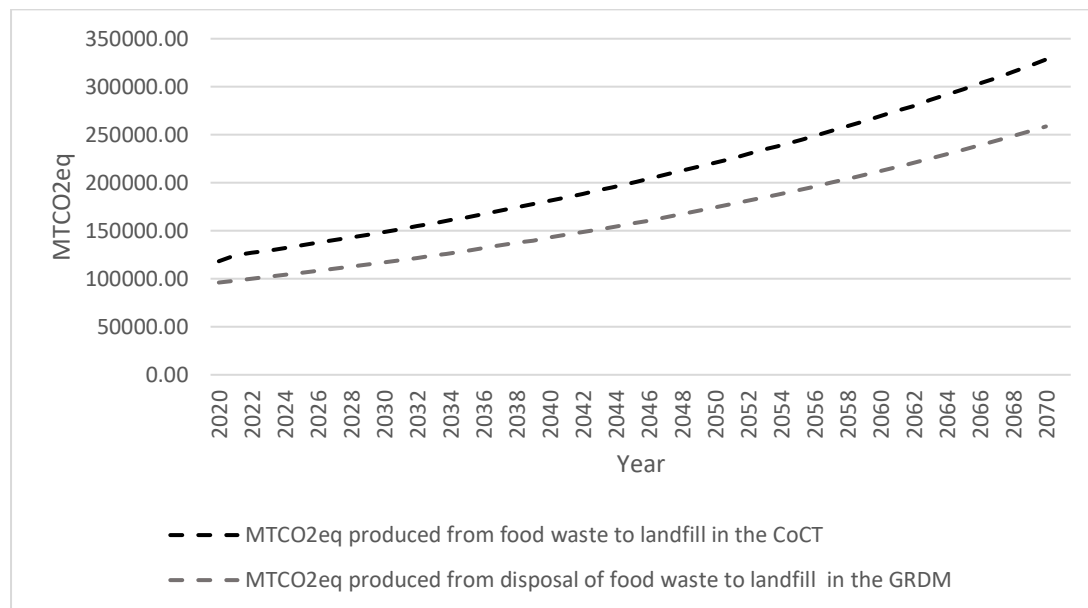
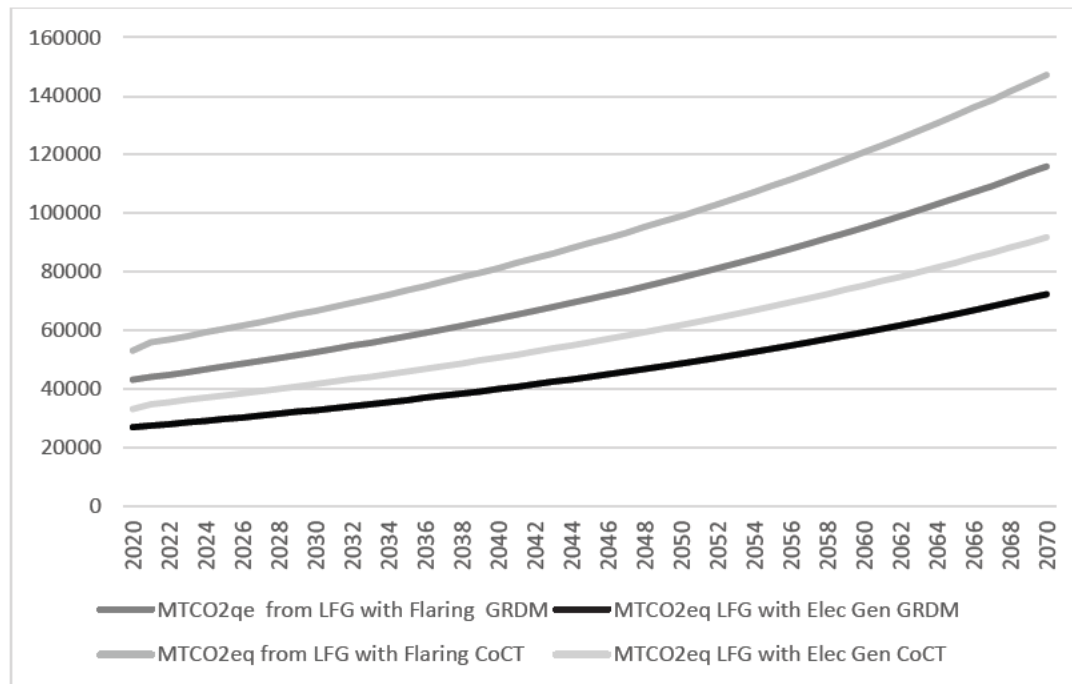


Figure 7. Methane emissions in MTCO₂eq produced from the disposal of food waste to landfill in the GRDM and CoCT over a 50 year period

Although the food waste fraction in the GRDM is higher at 25%, the MTCO₂eq emissions from the food waste disposed of to landfill is higher in the CoCT due to the higher population and higher waste disposal quantities. The food waste fraction in the CoCT equates to 8.1% of the total MSW fraction, yet the emissions produced from waste sent to landfill is higher than

the GRDM. The GHG emissions produced in the GRDM is estimated at 118242.17MTCO₂eq in the year 2020 and increases to 328354.98MTCO₂eq by 2070 should no interventions be put in place.

Figure 8 below considers the application of the advanced WROSE model on both of the case study municipalities for the use of landfill gas extraction technology to achieve emission in reduction firstly through flaring and secondly through the generation of electricity.



Landfill gas extraction has to potential to reduce GHG emissions from each of the case study municipalities by half when compared to disposal of waste to landfill with no gas extraction. The option of electricity generation has the potential to achieve higher emission reduction that that of flaring. Within the CoCT, there are currently two landfill facilities with gas extraction projects already implemented.

Figure 9 below depicts the total GHG emission reduction potential from the inputting the total food waste fraction to an anaerobic digestion facility. The GHG emission reductions from the total food waste fraction to AD is higher in the CoCT than the GRDM due to the higher waste tonnages. The GHG emissions reduction potential in the GRDM decreases from -2495.69MTCO₂eq in 2020 to -6717.38MTCO₂eq by 2070. Whereas the GHG emission reduction potential in the CoCT is higher than that of the GRDM through the disposal of the total food waste fraction to AD. The GHG emissions in the CoCT reduces from -

3071.22MTCO₂eq in 2022 to -8528.70MTCO₂eq. Although the potential emissions reduced over a 50 year period is significant through the simulation above, food waste fractions are not clean enough for use in AD facilities to allow for 100% extraction from landfill.

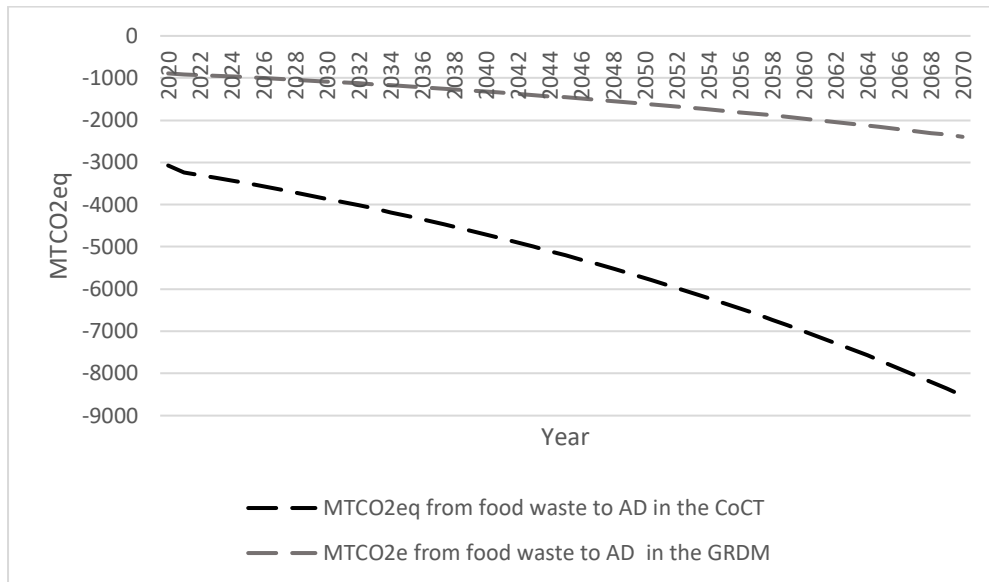


Figure 9. Methane emissions in MTCO₂eq reduced from food waste to AD in the GRDM and CoCT over a 50-year period

Further considerations were given to a phased approach at which the food waste fraction has the potential to be recovered at municipal level. This was considered with a minimum recovery rate of 5% and a maximum recovery rate of 40%. The phased approach forms the basis of the strategy for greenhouse gas mitigation over a 50-year period. Table 2 below outlines the percentage increment approach used for the organic waste recovery in the GRDM and CoCT over a 50-year period.

Table 2 :Phased GHG emissions at 5-year intervals for the CoCT and GRDM

Scenario	Phased Organic Waste Recovery Rate for GHG Emissions Reduction						
	2020	2025	2030	2040	2050	2060	2070
4a	0	5%	10%	20%	30%	40%	>40%

Figure 9 below depicts the emission reduction achievable through a phased waste recovery rate over 50 years with gradual increases every 10 year. Seeing as no recovery takes place from

2020 to 2025, no emission reductions are achieved. Thereafter emission reductions increase as the recovery rate increases in both the CoCT and the GRDM.

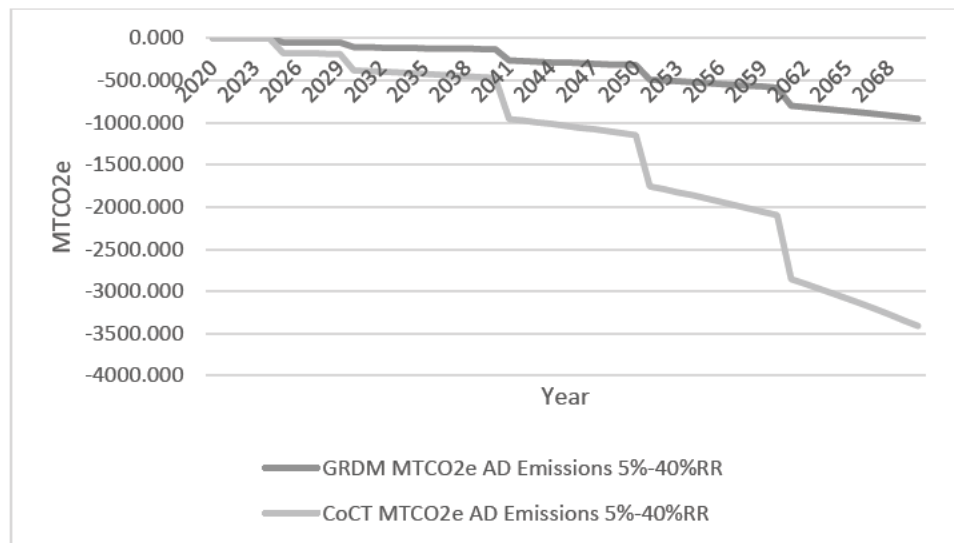


Figure 10. Methane emissions in MTCO₂e reduced from food waste to AD in the GRDM and CoCT over a 50-year period at a phased approach from 5%-40%.

In order for national targets to be met, greenhouse gas mitigation strategies need to be relevant to each level of government. Therefore, the strategy should embody short, medium and long term goals that translate into actionable tasks for municipalities to achieve emission reductions, the phased approach discussed above should be taken into consideration for the development of a greenhouse gas mitigation strategy. Using a multi criteria decision analysis technique and the information generated by the application of the advanced WROSE model, a climate mitigation strategy was developed for both of the case study municipalities. The strategy is developed taking into consideration the long term planning nature and life span of the proposed waste management technologies above. The strategy is proposed in the context of emissions reductions achievable at municipal level. The long term scenario projections output by the advanced WROSE model projects the potential for significant emissions reduction through both landfill gas extraction as well as anaerobic digestion. Taking this into consideration the table below was developed.

Table 3: Proposed framework for the development of a greenhouse gas mitigation strategy

Proposed framework for greenhouse gas mitigation strategy for South African Municipalities

Note: The proposed actionable steps below can be tailored to the needs of each municipality based on the availability of funding, amount of waste and size of facilities required.

Immediate term 0-5 years	Short term 5-10 years	Medium term 10-20 years	Long term 20-50 years
<p>Immediate term interventions include the optimization of the management of existing facilities. This also includes planning, proposals and feasibility studies for future infrastructure.</p> <ul style="list-style-type: none"> • Management of existing municipal waste management infrastructure to meet national standards • Ensure facilities are engineered and licensed • Conduct feasibility studies for the implementation of source separation for organic fraction and recyclables • Develop plans to recover 5% of the organic waste fraction for composting • Pilot small scale composting facility 	<p>Short term interventions are aimed at setting and achieving targets in a smaller time frame which will serve as a steppingstone to the larger goal of climate stabilization. These steps include but are not limited to:</p> <ul style="list-style-type: none"> • Development of a material recovery facility for gradually increasing waste recovery of organic waste • Implementation of wider scale separated collection for achieving a higher recovery rate of 10-20% • Lab scale pilot of AD facility • Plan and implement the development of a composting facility for organic waste • Plan the for development of an AD facility (micro, small or large scale pending the size of the municipality and available quantities) • Determine the biomethane potential of the recovered organic fraction for use in AD 	<p>Medium term interventions are key steps that provide direction for the implementation of the overall strategy. Medium term intervention examples include but are not limited to:</p> <ul style="list-style-type: none"> • Design and build large scale AD and composting facility. • Increasing recovery rate at MRF to 20-30% of organic fraction • Optimize system efficiencies overall 	<p>Long term interventions are key to establish integrated systems that can include more advance technology options.</p> <ul style="list-style-type: none"> • Management of a fully integrated waste management system which includes Separated collection, material recovery facility, composting and AD • Optimise recovery of >40% of the organic waste fraction at MRF

6.6 Conclusions

The purpose of this study was to forecast the potential GHG emissions from the organic waste fraction in the City of Cape Town and the Garden Route District Municipality. Thereafter to propose pathways to reduce emissions through the consideration of a portfolio of technology options which could reduce emissions. The purpose of this assessment is to guide the development of a framework which mainstreams climate mitigation considerations at the core of waste management decision making. The study involved conducting a comparative analysis of the GHG emissions and emissions reduction potential of food waste through the use of three WROSE scenarios, the disposal of food waste to landfill, landfill gas extraction with flaring and electricity generation and lastly, food waste to AD in each of the two case study municipalities, the CoCT and the GRDM. The key outcome of the study determines that in order for a greenhouse gas mitigation strategy to be successful, consideration needs to be given to the specific emissions achievable through the implementation of an integrated waste management system at metropolitan and district level in order to achieve optimal emissions reductions. This can also be translated to a local municipality level.

Furthermore, not all municipalities have the resources, human and financial to meet the targets set at national or provincial level. Therefore, a phased approach is required for the implementation of GHG emissions reduction strategies. The study therefore, proposed a framework which is aimed at allowing municipalities to meet the requirements of national targets with locally applicable actions geared towards GHG emission reduction. The framework incorporates immediate-term, short-term, medium-term and long-term interventions to achieve sustained carbon emissions from food waste at a district and metropolitan municipality. These can be adapted to suite the requirements at a local municipality level.

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Chapter 7

Conclusions and Recommendations

7.1 Introduction

This chapter summarises the key findings of the study and presents recommendations for the further development of research in the field. The foundation of this study is grounded in the fact that South African municipalities are solely responsible for the collection and disposal of municipal solid waste and, can therefore, contribute significantly to the reduction of emissions in the waste sector. The overarching aim of the study was to develop a framework that underpins climate change mitigation as a core factor in decision making, through the identification of appropriate pathways which are applicable at municipal level but would ultimately contribute to achieving national emission reduction targets such as the NDCs. The purpose of the study was to strengthen the way South Africa conducts GHG accounting by transitioning from a Tier 1 to a Tier 2 approach. The Tier 2 approach employed IPCC emission factors with the WROSE model which is specifically designed for South Africa.

In order to meet the aims of the study, the following objectives were specific to the study:

- The selection of two case study municipalities, the City of Cape Town and the Garden Route District Municipality.
- The identification of appropriate GHG emission mitigation pathways applicable to South African Municipalities using the WROSE model.
- Collection of waste stream analysis and waste composition data from the IWMPs of each of the case study municipalities.
- The calculation and forecasting of emissions and potential emission reductions from 2020 to 2070 for the organic waste fraction in each of the case study municipalities.
- The development of a framework to achieve greenhouse gas mitigation in a phased approach at municipal level that will ultimately contribute to meeting national emission reduction targets.

In achieving these objectives, this study will enable decision makers at municipal level to harmonise with the targets set by policy makers at national levels. This bottom up approach, using country specific models such as the WROSE model allows for actionable tasks to be set relevant to the quantities of waste and infrastructural needs of the municipality.

7.2 Key findings and conclusion

The key findings of the study align with the research questions proposed in Chapter 1.

In answering Research Question 1, the study first looked at the IWMP's of both municipalities to understand the availability of data on the organic waste fraction of each municipality. Thereafter, the WROSE model was advanced using an algorithm developed to enable the model to conduct long term greenhouse gas forecasting. This long term forecasting included waste tonnage estimates which were established using the most recent waste characterisation studies conducted at each municipality which aligned with the population growth in each of the case study municipalities. These tonnages, input into the advanced WROSE model were then used to project the potential GHG emissions that could occur from the organic food waste and garden refuse components should they be sent to landfill over a 50 year period. The climate contributions identified for each of the case study municipalities were of significant proportion, almost triple the current emissions, should the municipalities continue with the disposal of these fractions to landfill. Lack of current, reliable data emerged as a key constraint to the study, this contributes to a level of uncertainty in the assumptions made. This highlighted the need for the standardisation of waste data collection and reporting that is required at municipal level.

In answering Research Question 2, the study proposed pathways for the mitigation of greenhouse gases from the organic waste fraction, through the introduction of a portfolio of applicable technology options. These options are, the disposal of organic waste to landfill, which is still the most widely used method of waste management in South Africa, followed by the disposal of waste to landfill, with landfill gas extraction and flaring or electricity generation. Lastly the third proposed technology option, applicable to the treatment of organic waste is the use of anaerobic digestion technology. Another important finding of the study, however, is that municipalities do not currently have the necessary systems in place or the necessary infrastructure to implement immediate GHG emission reduction strategies.

This links directly to answering Research Question 3, whereby the proposed technology options, cannot be used in isolation but rather as part of an integrated system that could achieve maximum GHG emissions reduction. Therefore the framework proposed takes into consideration the current infrastructure and capacity of each of the case study municipalities

along with the nature of the South African governmental landscape and financial cycles to proposed a step by step approach to climate mitigation. Therefore, this study proposes a framework for the phased application of greenhouse gas mitigation strategies for organic waste fractions in the MSW sector.

7.3 Limitations of the Study

Two key limitations were identified in course of this study the first being the reporting of waste data which differs from one municipality to the next which results in inconsistencies in how municipalities classify waste streams and collect waste data e.g. weighbridge data versus waste characterisation data.

The second limitation is the use of outdated waste characterisation data in municipalities to predict current and future waste generation trends. Therefore, specific boundary conditions needed to be assigned to each of the studies conducted.

7.4 Recommendations

Through this study GHG emissions are predicted to rise exponentially without any interventions over the next 50 year. Therefore, it is important to understand how GHG emissions are calculated. In order to do so, such research is heavily reliant on good quality data. However, to date many South African municipalities do not have the financial, technical or human capacity to conduct regular waste stream analysis and therefore data collection.

Therefore, the need for more reliable waste data to determine GHG emissions as well as potential GHG emission reduction capacity, gives rise to the need for norms and standards for waste data collection and characterisation. Further studies should be conducted into the optimization of municipal waste management processes to meet minimum legislative requirements. Furthermore, studies should assess the potential for the embedding of standardised waste characterisation and data collection into the National Environmental Management: Waste Act and/or the National Waste Management Strategy .

Furthermore, although the WROSE model is effective as a priority framework for waste management technologies, the model does not incorporate preventative strategies such as waste prevention, minimization or systems to maximize reuse and recycling. Therefore further model development is recommended for the incorporation of all levels of the waste hierarchy. This

will further assist municipalities in meeting GHG emission reduction targets through broadening the focus beyond waste treatment and to incorporate preventative waste management strategies. In assessing waste minimization and prevention measures, it is further recommended that other factors such as GDP be taken into account for further advancement of the WROSE model when determining waste generation in the context of waste minimization and prevention in the shift towards a circular economy.

Lastly the proposed framework for achieving greenhouse gas mitigation should be further unpacked. This type of framework has the potential to inform waste management planning and decision making, from a climate change mitigation perspective. It is recommended that such a framework be tested at municipal level when developing policies and plans for integrated waste management, spatial development, integrated development planning. It is recommended that the outcome of such an application could feed into future NDC plans for South Africa to meet the GHG national emissions reduction targets.

ANNEXURE A

PLASTIC WASTE MANAGEMENT FOR LANDFILL SPACE SAVINGS AND GHG EMISSION REDUCTION IN THE GARDEN ROUTE DISTRICT MUNICIPALITY

The paper below has been incorporated as waste diversion also has the added value of landfill space savings that can be achieved at municipal level. This paper was published at the WasteCon 2022 conference proceedings as per the citation below:

Kissoon, S. and Trois, C. 2022. Plastic waste management for landfill space savings and GHG emission reduction in the Garden Rout District Municipality. WasteCon 2022.

ABSTRACT

The recycling of plastic packaging materials has expanded rapidly over the years. This is due to an increase in technological advancements and the awareness of materials widely available for recycling. Through combined efforts from government, industry and the general public, larger amounts of plastic waste have the potential to be removed from the municipal solid waste stream and has the ability to further enhance the recycling market in South Africa, thereby contributing to landfill airspace savings. The aim of this study is to determine the potential landfill diversion rates and landfill airspace savings that can be achieved through the extraction of low density polyethylene (LDPE)and polyethylene terephthalate (PET) plastic polymer fractions from the municipal solid waste stream over a 50-year period using the Garden Route District Municipality as a case study. In addition, the GHG emissions and emission reduction will also be included. The study employs the Waste Resource Optimization and Scenario Evaluation (WROSE) model as a methodology to select the scenarios that will be assessed. The scenarios identified were, the collection and disposal of unsorted untreated MSW as the business-as-usual scenario. The second scenario was the collection of unsorted, untreated MSW to a mechanical pre-treatment facility and ultimately recycling. The outcome of the study derived a 1.5% diversion rate from landfill when considering the extraction of the PET and LDPE fractions as a whole from the total waste generated. Landfill space savings are seen to increase as larger amounts of PET and LDPE are extracted from landfills. GHG emissions are low in the business as usual scenario due to emissions from the disposal of LDPE and PET to

landfill being contributed to from the transportation of plastic waste. However, GHG emission reductions are seen when PET and LDPE fractions are extracted.

INTRODUCTION

The management of municipal solid waste (MSW) continues to pose an important environmental challenge. The collection and disposal of MSW to landfill contributes to greenhouse gas (GHG) emissions and subsequently the overall impact on global warming. Constantly increasing amounts of MSW combined with limited landfill airspace in South Africa has led to the need of the consideration of alternative waste management mechanisms to reduce the burden on landfills. According to the State of Waste Report, 2018, of the total plastic waste generated in South Africa, only 43.7% was extracted for recycling while the remaining 56.3% was disposed of into landfill. As per the WWF plastics report in 2020 the average plastic consumption is 36kg per capita per year in South Africa. Consequentially the consideration of alternative waste management contributes to the potential reduction of GHG emissions from the collection and disposal of plastic waste.

The strategies identified in this study contribute to the diversion of waste from landfill as well as landfill space savings. This is for the purpose of the production of new products which has the potential to activate better waste to resource management and contribute to the circular economy.

The aim of this study is to conduct simulations of the diversion of LDPE and PET plastic waste fractions from landfill to determine potential landfill space savings in the Garden Route District Municipality over a 50-year period. Thereafter simulating the impact of interventions such as recycling on the reduction of GHG emissions. This will be achieved through illustrative scenarios of the diversion of PET and LDPE plastic from landfill at various rates, thereby establishing the potential landfill space saving and GHG emission reductions that can be achieved.

Due to a lack of reliable, available data, specific boundary conditions needed to be assigned in order to achieve the aim of the study.

4. Historical Integrated Waste Management Plan (IWMP) and Integrated Development Plan (IDP) data was extracted and utilized for the forecasting of total population and waste generation figures.

5. Population growth was established at 2% per annum based on the projections conducted by the Department of Social Development in the Garden Route District Municipality in line with the district.
6. Average waste characterisation percentages were extracted from the 3rd generation IWMP for determining waste fractions in tons.
7. National average recycling figures were employed to determine the amount of plastics that were extracted for recycling and what would be sent to landfill.
8. Only LDPE and PET fractions of plastics were considered for the purpose of this study as they are statistically the most recycled plastic polymer fractions in South Africa.

LITERATURE REVIEW

According to the State of Waste Report 2018, plastic waste accounts for 2% of the total general waste stream generated in 2017. In 2019, 503 600 tons of plastic waste was collected for the purpose of recycling this includes packaging and imported recyclables from neighbouring countries (SAPRO, 2019). South Africa has an input recycling rate of 46.3% for all plastics in 2018. More than 70% of the recyclable plastics collected were sourced from landfills and post consumer waste. Furthermore, the plastics recycling sector contributes 2.3% to the South African GDP and up to 18.5% of the manufacturing GDP (SAPRO, 2019). According to the South African Plastics recycling survey conducted in 2019 by Plastics SA, 244 300 tons of CO₂ were saved.

Global production of plastics grew from 2Mt to 390Mt between 1950 and 2015 (Zheng, 2019) Globally 58% of plastic waste is discarded of into landfill and 18% was recycled in 2015. Although there are concerns globally of the impact of plastics on the environment as well as human health, very little research is done on the contributions of plastic waste on climate change and GHG emissions (Zheng, 2019). One of the explored strategies for the reduction of GHG's from plastic waste is recycling which partially reduced the carbon intensive virgin polymer production (Zheng, 2019).

MSW management as a whole contributes significantly to GHG emissions (Calabrò., 2009). Plastics as a material contributes to environmental impacts in multiple ways, the production of plastics contributes to GHG emissions. The wide use of plastic materials contributes to a growing waste management problem (Sevigné-Itoiz *et al.*, 2015). In order to reduce emissions

and increase the lifespan of landfill facilities an integrated approach must be used (Calabrò., 2009). According to Plastics SA, the most widely recycled plastic material in South Africa are low density polyethylene (LDPE) and polyethylene terephthalate (PET). Therefore, for the purpose of this study the LSS and GHG emissions and emissions reductions will be illustrated for the LDPE and PET polymer fractions.

STUDY AREA

The Garden Route District Municipality (GRDM) is located in the Western Cape Province, South Africa. The GRDM is at present the third largest District in the Western Cape and is home to 7 local municipalities. These are, George, Knysna, Bitou, Mossel Bay, Kannaland, Hessequa and Oudtshoorn. The total surface coverage of the GRDM is approximately 23 332km² (GRDM IDP, 2019). Around 80% of the population within the GRDM resides in Urban Areas. According to the Department of Social Developments Projections the GRDM total population was at 635 600 in 2019 with a provincial population growth of 2% per annum (GRDM IDP, 2019).

In 2019 the GRDM conducted a waste characterisation study of the MSW at household level. The outcome of the waste characterisation study is outlined in the figure below. Food waste comprised 25% of the total waste profile whereas recyclables accounted for 40.3% of the total domestic waste profile, this includes hard and soft plastics, glass, metals, paper and cardboard (Gibb, 2020). The combined plastic waste fraction accounts for 16% of the total waste profile which is the second highest waste stream to food waste.

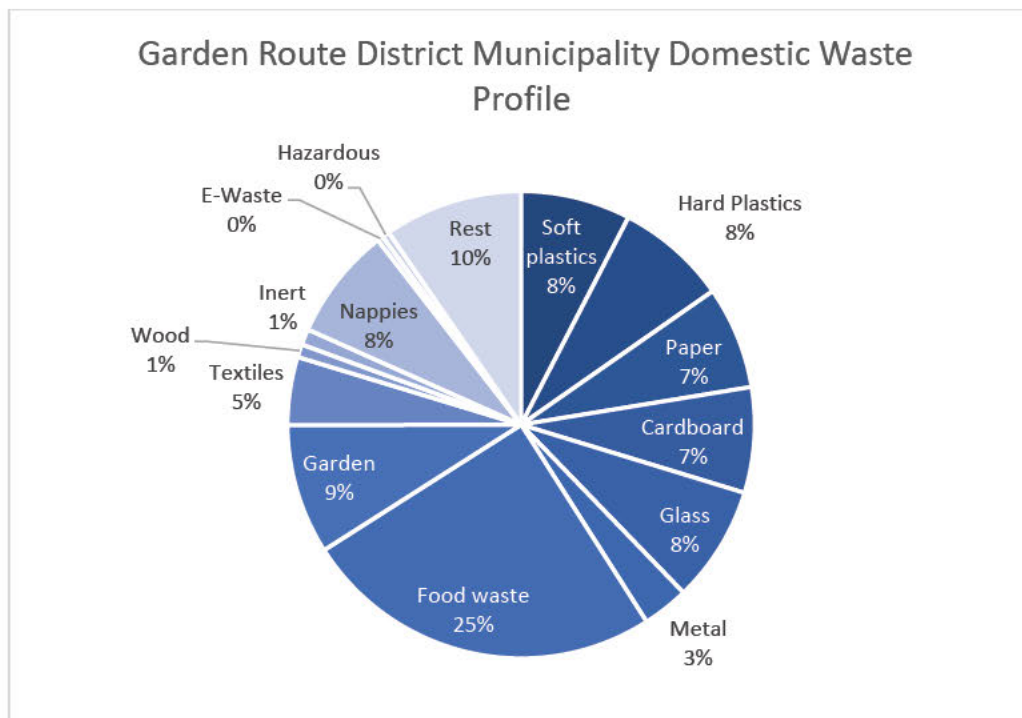


Figure 1: Garden Route District Municipality Domestic Waste Profile (Gibb, 2020).

METHODOLOGY

In order to achieve the objectives of the study, landfill density factors were used to determine landfill airspace that could be saved by the extraction of PET and LDPE of plastics. Three types of calculations were conducted for this study. Firstly the landfill diversion rates were simulated for the extraction of the PET and LDPE fractions. Secondly the landfill space savings were established using the USEPA density factors. Lastly GHG emissions and emission reductions calculations were conducted to determine how much GHG emission reductions could be achieved through the extraction of LDPE and PET from landfill.

The Waste Resource Optimisation and Scenario Evaluation (WROSE) model is a methodology developed by the University of KwaZulu-Natal to aid municipalities in the decision-making process as a zero waste and GHG emissions reduction model. The WROSE model is used to assist municipalities in aligning with national legislative requirements and achieving sustained waste and emissions reduction through the evaluation of integrated waste management scenarios upon all levels of sustainability (environmental, economic, social and institutional). A number of scenarios are embedded in the WROSE model, ranging from baseline (business as usual) to more complex optimised solutions. Figure 2 below outlines the scenarios of the

WROSE model graphically. The WROSE model uses waste volumes of each waste fraction generated as input data, the outputs of the model are methane emissions productions or reductions. The outputs of the model are not limited to methane emissions but rather expand to a range of indicators such as landfill airspace savings (LSS), economic indicators, job creation potential, health risks associated with the jobs created, and institutional indicators.

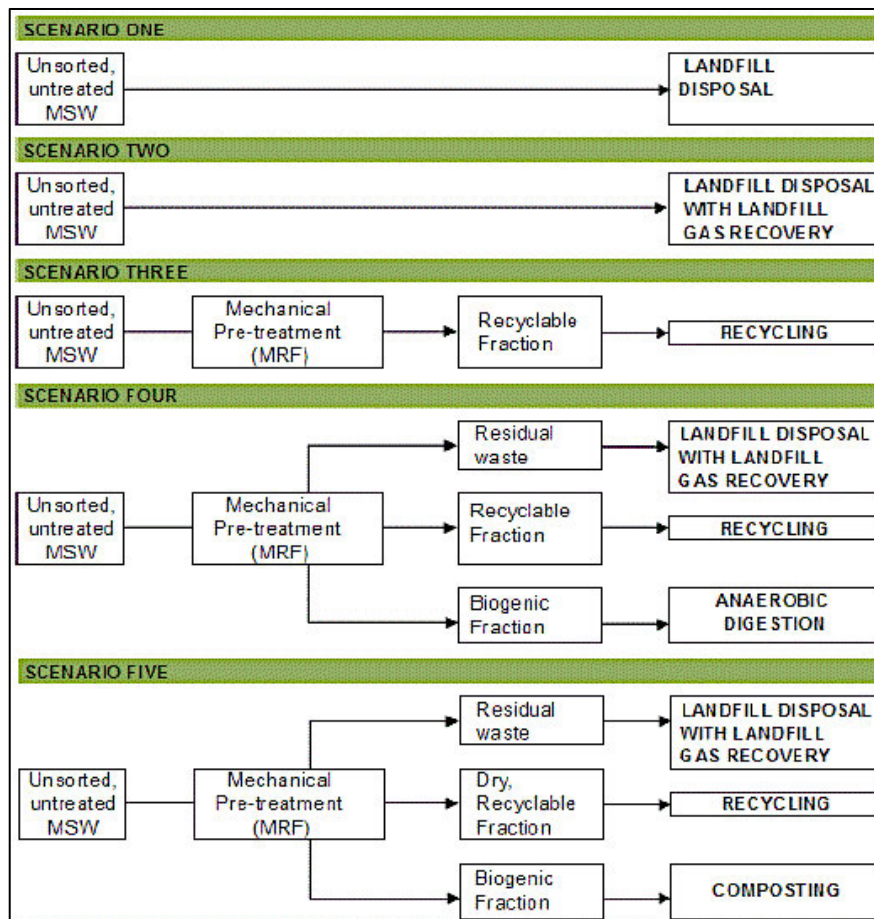


Figure 2. WROSE scenarios schematic (Jagath & Trois 2011)

For the purpose of this study, the WROSE model was utilised for the selection of the scenarios that were assessed. Due to plastics waste management forming the core focus area of the study, the scenarios identified as most applicable to this study are:

For this study 2 scenarios were considered:

6. SCENARIO 1: The disposal of unsorted, untreated MSW to landfill (BAU)
7. SCENARIO 3: Unsorted and untreated MSW undergo a mechanical pre-treatment with recovery of recyclable fraction through a Materials Recovery Facility (MRF)

Of the total plastic waste fraction established in tons, the amount of PET and LDPE were extrapolated based on the Plastics SA recycled figures as per the pie chart below.

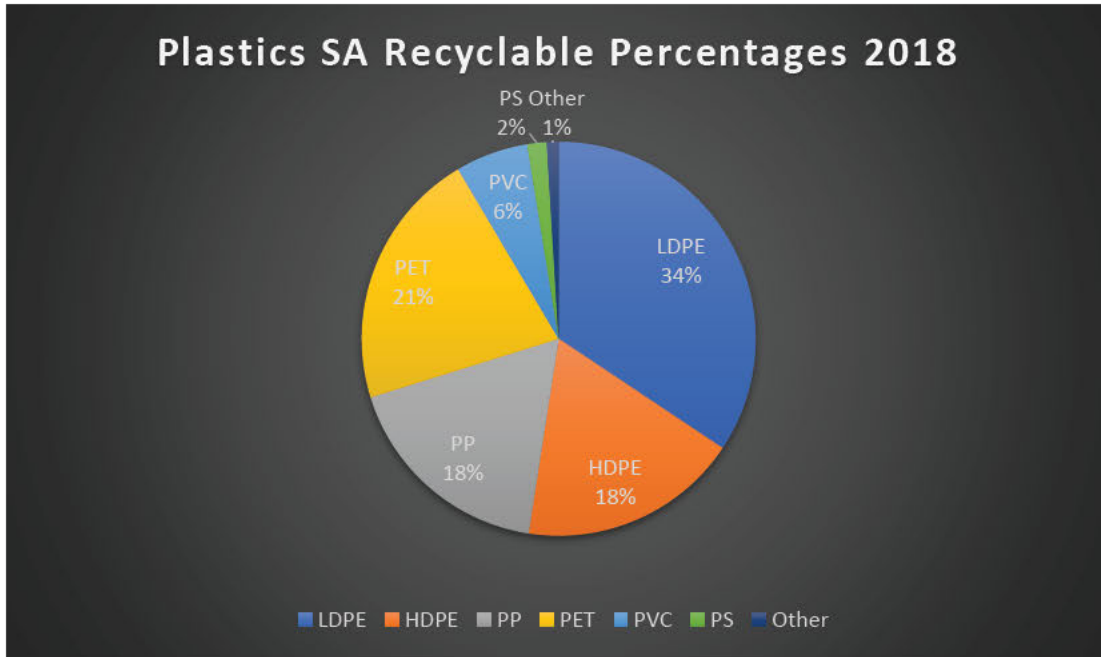


Figure 3. Plastics SA recyclables percentage per polymer fraction

Using the polymer fractions of PET at 21% of the total plastic waste fraction and LDPE at 34% of the total plastic polymer fraction, the tonnages were determined as input data for the LSS and waste diversion rates. Equation 1 below was used to simulate the landfill space saving potential that could be achieved through the extraction of PET and LDPE fractions.

$$\text{Landfill Space Saving } m^3 = \frac{\text{Total waste quantity diverted (tons)}}{\text{Average compacted density of mixed MSW}}$$

Equation 3. Landfill space savings calculation

In order to determine the waste diversion rates the equation below was used.

$$\text{Diversion rate} = \frac{\text{Waste diverted (tons)}}{\text{Total waste generated (tons)}} \times 100$$

Equation 2. Waste diversion rate calculation

In addition, methane emissions or emission reduction potential which were calculated in MTCO₂eq using the IPCC derived USEPA 2016 emission factors.

The equation below was used to determine the methane emissions or emission reduction potential in MTCO₂eq :

$$\text{Waste volume in tons} \times \text{emission factor} = \text{MTCO}_2\text{eq}$$

Equation 3. Emissions from waste management scenarios in metric tons of CO₂eq

These emissions/emission reductions and landfill space savings were calculated for a 50-year period for each of the defined scenarios selected using the appropriate emission and density factors. Taking into consideration that the total amount of LDPE and PET tons may not be viable for recycling due to contaminants in the waste stream, assumptions were made for determining viability of LDPE and PET fractions for recycling. Simulations were conducted at 10% intervals up to 40% assuming that due to contamination only a portion of the LDPE and PET streams are viable. The results for which are discussed in the section below.

RESULTS AND DISCUSSION

Plastic waste accounts for 16% of the total waste generated for consideration in the study. LDPE and PET account for 55% of the total plastic waste stream. Using the calculation above the waste diversion rate was established at 1.5% of the total waste stream should the entire LDPE and PET fractions be extracted.

Figure 4 below depicts the landfill space saving that can be achieved through the diversion of PET from landfill at various achievable intervals by the year 2070. The potential recycling rates were simulated based on the volume of PET plastics that are viable for recycling. These were at 10%, 20%, 30% and 40% of the total PET fraction. The higher the percentage of PET extracted for recycling, the greater landfill space saving potential.

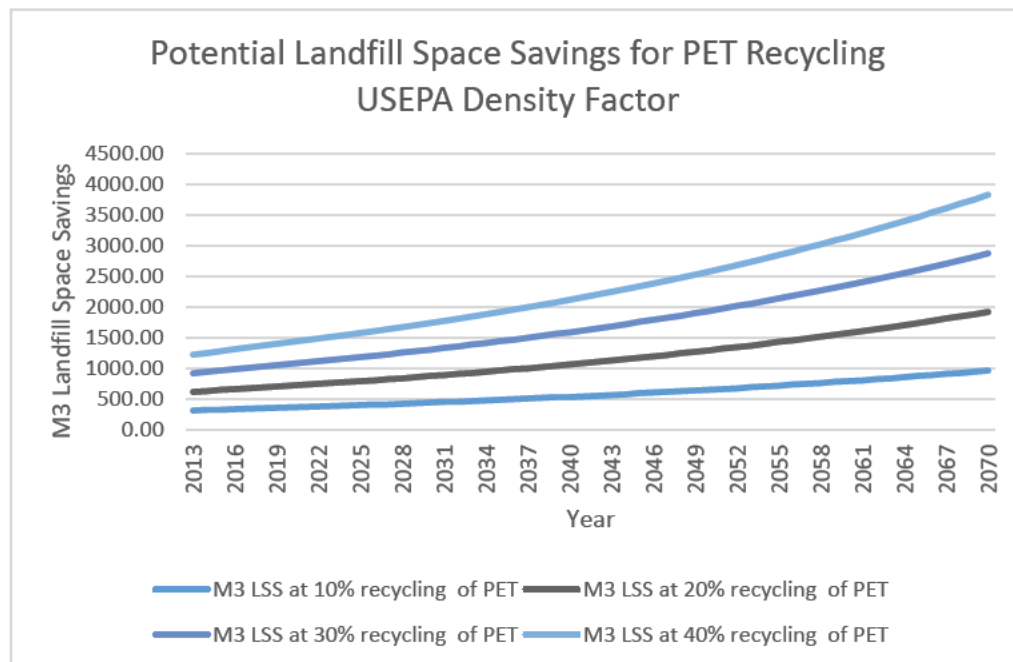


Figure 4. Potential landfill space savings for PET recycling over 50 Years in the Garden Route District Municipality

The figure below illustrates the BAU scenario as increasing GHG emissions over the next 50 years from 55.29 MTCO₂eq in 2013 to 173.96 MTCO₂eq in 2070. The disposal of PET does not contribute directly to GHG emissions as there is no degradation of organic matter. However, the GHG emitted and accounted for is due to the transportation of plastic waste. The extraction of the PET fraction for recycling through Scenario 3 at various intervals, depicts the reduction of GHG emissions.

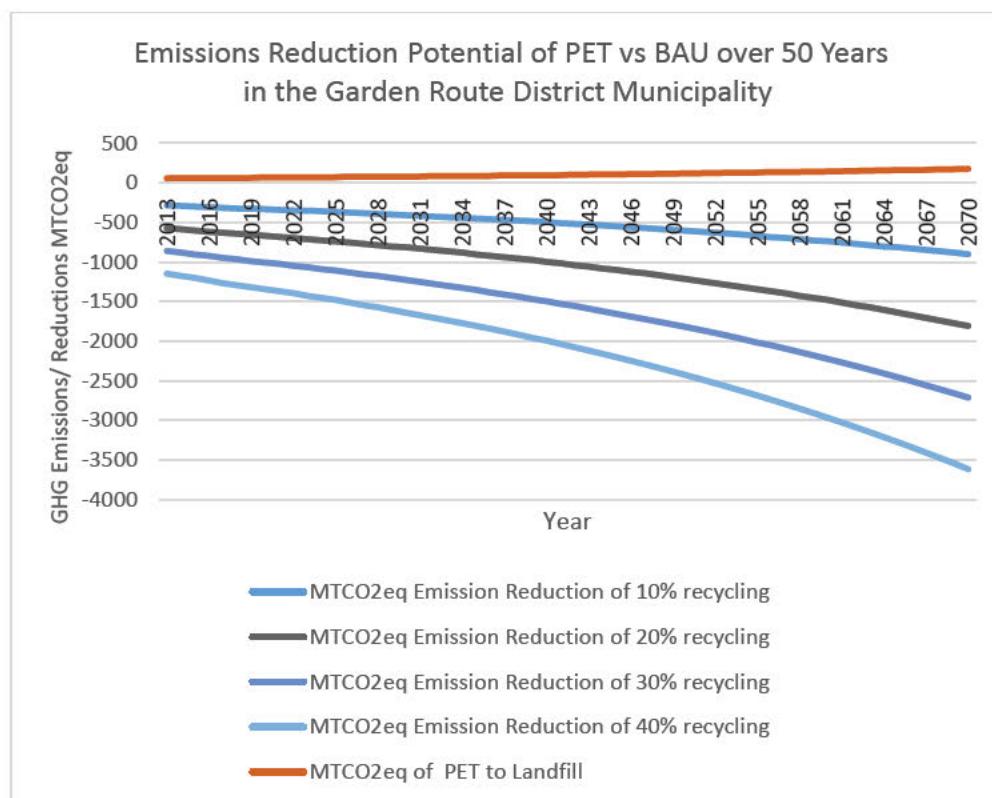


Figure 5. Emissions Reduction Potential of PET vs BAU over 50 Years in the Garden Route District Municipality

Figure 6 below depicts the landfill space saving that can be achieved through the diversion of the LDPE fraction from landfill at various achievable intervals by the year 2070. The potential recycling rates were simulated based on the volume of LDPE plastics that could potentially be viable for recycling. These simulations were considered at 10%, 20%, 30% and 40% of the total LDPE fraction. The higher the percentage of LDPE extracted for recycling, the greater landfill space saving potential.

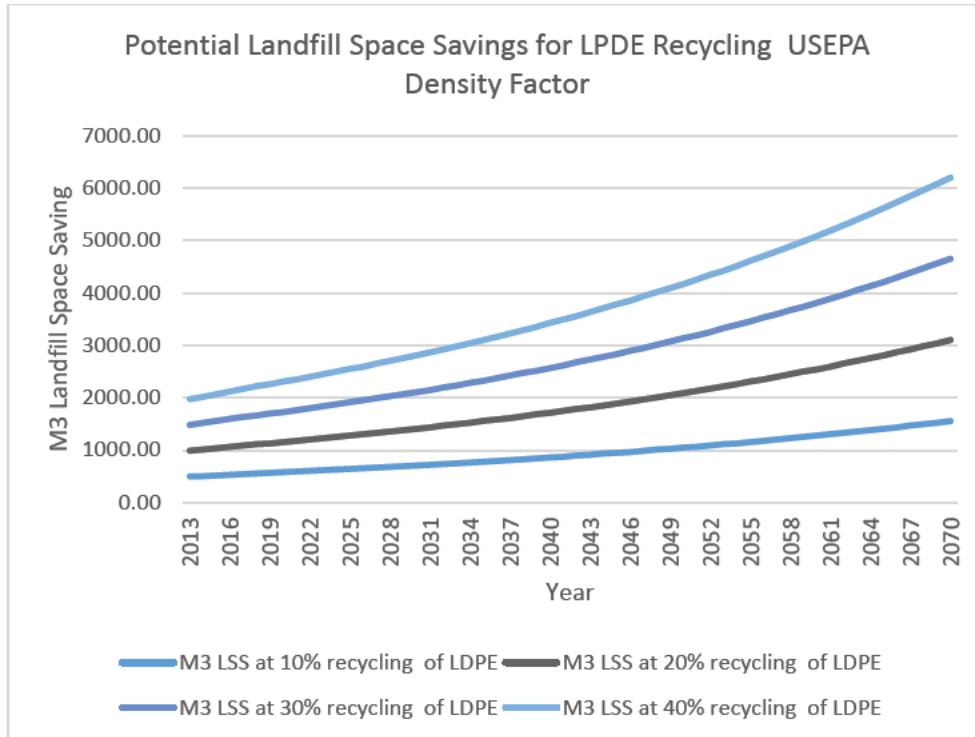


Figure 6. Potential landfill space savings for LDPE recycling over 50 Years in the Garden Route District Municipality

Similarly, to that of PET, the contributions of LDPE’s disposal to landfill increases over the next 50 years from the transportation of LDPE. The figure below illustrates the BAU scenario as increasing GHG emissions over the next 50 years from 89.58 MTCO₂eq in 2013 to 281.65 MTCO₂eq in 2070 through the disposal of LDPE to landfill. However, the extraction of the LDPE fraction for recycling through Scenario 3 at various intervals, depicts the reduction of GHG emissions.

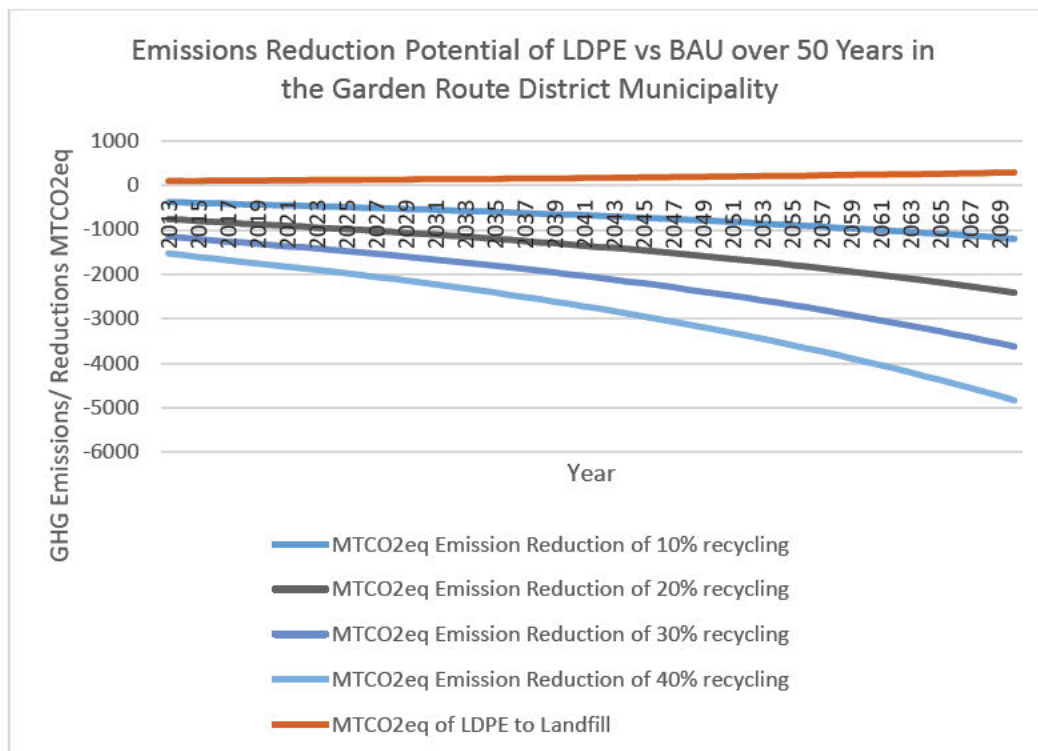


Figure 7. Emissions Reduction Potential of LDPE vs BAU over 50 Years in the Garden Route District Municipality

CONCLUSION

Using the WROSE model, 2 scenarios were identified as relevant to this study. These are Scenario's 1 and 3. This study comprised of 3 key components. The first being the estimation of the landfill space savings that could occur through the diversion of LDPE and PET fractions from the municipal solid waste stream generated in the Garden Route District Municipality. The second component was to determine the waste diversion rate and lastly the determination of GHG emission reductions as a result of the diversion of PET and LDPE. The outcome of the study yielded similar results for both the PET and LDPE fractions. The landfill space savings would be higher as larger amounts of plastics are extracted from the municipal stream. However due to LDPE and PET only accounting for a small fraction of the overall waste generated and only 16% of the total recyclable fraction the landfill diversion rate is low at 1.5%. There is potential for GHG emission reductions however this is due to transportation and energy savings as a result of not having to produce virgin materials.

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